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THE GRAPHITE DEPOSITS OF CEYLON. A REVIEW OF PRESENT KNOWLEDGE WITH A DESCRIPTION OF A SIMILAR GRAPHITE DEPOSIT NEAR DILLON, MONTANA.[1]

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INTRODUCTION.

The graphite deposits of Ceylon are of especial interest to Americans because most of the graphite used in this country comes from that island and because the United States has for many years been the largest consumer of the Ceylon material. Much has been printed in regard to these deposits, but it is widely scattered through publications in various languages which are not readily accessible to the American public. The writer has thought it worth while, therefore, to summarize the more important facts which are on record with apologies for any errors or oversights due to his lack of personal knowledge of the island.

Although their existence was known in early times and mentioned in print as early as 1681, the graphite deposits of Ceylon were not exploited until sometime between 1820 and 1830. In 1829 Joseph Dixon is reported to have imported a small amount into the United States, but it was only in 1834 that the industry assumed commercial importance. From that time to this, as a result of the growth of metallurgical industries, and the resulting

[1] Published with the permission of the Director of the United States Geological Survey.

demand for refractory materials, the industry has developed rapidly, until at present graphite is subordinate in value only to tea and the products of the cocoanut palm among the exports from the island. The diagram below shows the production

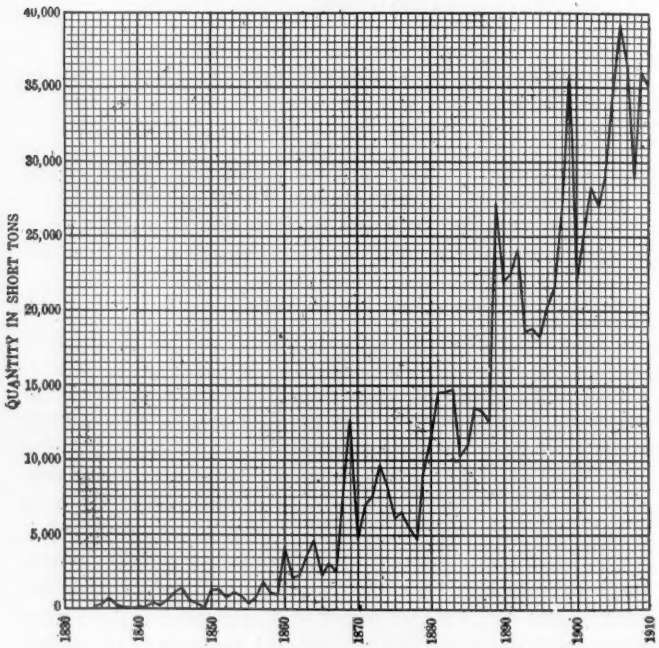


FIG. 60. Diagram showing the quantity of graphite (plumbago) exported from Ceylon from 1834 to 1910. (From the *Journal* of the Royal Asiatic Society, Ceylon Branch, Vol. 9, pt. 2, 1885, and the Ceylon Blue Books.)

of graphite in Ceylon from 1834 to 1909. From the early days of the industry up to 1901 Great Britain consumed more Ceylon graphite than any other country. Since 1901 the United States has assumed the first place with Great Britain second until

1909 when Germany took second place. The distribution of graphite exports for one year in each of these trade periods is given below.

EXPORTS OF GRAPHITE FROM CEYLON, IN SHORT TONS.

	1885.	1902.	1911.
Great Britain	7,670	7,586	5,794
Unites States	3,074	15,244	12,062
Germany	67	3,833	8,572
Belgium		1,096	3,108
Others	187	453	695
Total	10,998	28,212	30,231

It is interesting to note that an American concern, Pettinos Bros., of Bethlehem, Penn., is one of the principal exporters of Ceylon graphite. With the exception of the operations of this concern, and of a limited amount of graphite mining done on tea estates, the industry is in the hands of native Sinhalese. It has been estimated that the various processes of mining, sorting, "curing," packing, and shipping graphite as well as the making of barrels in which it is exported provide employment for about 50,000 men, women and children.

The island of Ceylon (Fig. 61) lies just off the southern point of the peninsula of British India, the channel between being nowhere deep enough for the passage of large ships. The island is more or less pear-shaped in form, and has a length from north to south of about 275 miles, and a maximum width of about 135 miles. A railroad extends along its entire length with branches into the central interior. Colombo, the Capital and principal seaport, is on the western coast, and is the port from which nearly all of the graphite is shipped; a small amount is shipped from Galle.

The island may be divided into two natural provinces, a mountainous region of crystalline rocks which forms the southwestern part of the island and a lowland area made up of coral limestones and marine sands of much later origin. In the mountainous province there are ten peaks which rise to elevations of over 7,-

FIG. 61. Map of the Island of Ceylon, showing the location of graphite mines. (Adapted from Stonier.)

000 feet, the highest being 8,296 feet. This province covers about one fifth of the area of the island, and in it are located all of the graphite deposits. The principal mines, as shown in Fig. 528, are in the southern, western, and northwestern provinces and in the province of Sabaragamuwa, at distances of from 5 to 50 miles from the sea. The deepest and best graphite mines are near Kurunegale in the northwest province; others are located near Kegalla, fifteen miles or so to the south and near Ratuapura, both in the province of Sabaragamuwa. The relative importance of the various districts may be judged from the following data taken from the Ceylon Blue Book for 1909:

DISTRIBUTION OF GRAPHITE MINES IN CEYLON IN 1909.

Province.	District.	Number of Graphite Pits.	Output in Long Tons.
Sabaragamuwa	Ratnapura	188	7,351
	Kegalla	53	4,041
Southern	Galle	170	5,026
	Matara	73	——
Western		248	4,763
Northwestern	Kurunegale	38	2,432
Central	Kandy	——	394
	Totals	770	24,007

ROCKS ASSOCIATED WITH GRAPHITE DEPOSITS.

The most abundant rocks of the mountainous crystalline area are gneisses (true gneisses and granulites of the European geologists) of varieties both light (acid) and dark (basic). The foliation of these rocks strikes in general northwest and southeast, and is responsible for the northwest-southeast trending valleys and ridges which form a conspicuous feature of the topography of the hilly province. Conspicuous jointing nearly at right angles to the foliation has determined the position of many of the tributary valleys.

Gneisses which are nearly pure quartz grade into others which contain small quantities of feldspar, garnet and mica. Other types consist mainly of quartz and orthoclase feldspar with garnet and biotite as accessory and zircon, apatite and graphite as

occasional constituents. More basic types are composed mainly of labradorite feldspar with either pyroxene (hypersthene) or hornblende. The most basic varieties usually form lenticles or pinched bands among the acid and medium types and show as their principal constituents hypersthene, augite, garnet, basic plagioclase feldspar, etc. Intimately interbanded with the commoner types of gneiss in bands varying in width from a few inches to hundreds of yards are crystalline limestones, many of which are dolomitic. The origin of the gneisses is not certainly known but the presence of beds of crystalline limestone will be regarded by most geologists as proof that a part of them at least are metamorphosed sediments. The presence along certain contacts between limestone and gneiss of rocks composed mainly of diopside, mica (phlogopite, etc.) amphibole, scapolite, spinel, sphene and cacite with occasional feldspar, marcasite, etc., is on the other hand, suggestive of contact metamorphism and hence, of an igneous origin for certain of the gneisses.

Other rocks from the southwestern part of the island, described under the name of the Galle group, are particularly rich in lime-silicate minerals. In addition to quartz, green pyroxene and feldspar they contain wollastonite, scapolite and sphene and sometimes apatite, garnet, zircon, pyrite and graphite and they show conspicuous banding. Microscopic sections show that the graphite crystallized at the same time as the other rock minerals. The association of minerals present in them is certainly suggestive of contact metamorphic origin. Certain rocks of the same Galle group are massive and consist mainly of quartz, orthoclase and wollastonite. They form irregular patches or vein-like masses which may cut across the trend of the banded types and are often exceedingly coarse, containing wollastonite individuals up to 36×15 inches, quartz up to $11 \times 5\frac{1}{2}$ inches, and orthoclase crystals up to 24 inches in diameter. The rocks are possibly to be regarded as true pegmatites, which have absorbed lime from sediments with which the magma has come in contact. The writer has observed wollastonite at Apex, Colo-

rado, in an abnormal phase of a monzonite porphyry intrusive in calcareous schists of sedimentary origin.[1]

In the absence of any fossils, the age of the gneisses and associated crystalline limestones can only be inferred from the relations observed on the neighboring mainland of India. There as we proceed southward the palæozic rocks disappear and are succeeded by rocks believed to be pre-Cambrian, which are closely similar to the crystalline rocks of Ceylon.

The ground mass of foliated rocks has been intruded by massive igneous rocks of both acid and basic varieties. Prominent among the acid varieties are zircon granite and granite pegmatites. The granite consists mainly of quartz, orthoclase and acid plagioclase feldspars, and biotite, with zircon, ilmenite and and apatite as accessories. Clear, colored zircons from this granite found in placers are sold as gems. The pegmatites consist essentially of orthoclase and quartz (often in graphic intergrowth) with subordinate mica or hornblende or both; allanite, apatite, ilmenite, tourmaline, and uraninite are sometimes present. The pegmatites may cut across or parallel the foliation planes of the gneisses.

The basic varieties of igneous rocks include pyroxenites of several varieties. The relationship of some of these to the gneisses leaves no doubt of their intrusive character which is well shown in Fig. 62 below, but the descriptions lead one to suspect that truly intrusive pyroxenites have not always been differentiated from pyroxenic rocks of contact or of dynamic metamorphic origin, occurring as nodular aggregates in crystalline limestone or forming contact zones between limestones and gneisses.

THE GRAPHITE DEPOSITS.

In regard to the occurrence of the graphite, the mineral has been found locally in small amounts disseminated in the crystalline limestones and some of the gneisses but the commercially important deposits are all vein-like in character and were de-

[1] Bastin, E. S., and Hill, J. M., "The Evergreen Copper Mine, Colorado." Economic Geology, Vol. VI., p. 471, 1911.

posited along fracture planes in the rocks. They are thus distinctly later than the rocks which they traverse. In most of the graphite districts the main veins parallel the foliation planes of the gneisses, thus striking northwest and southeast. In the Kurunegale district, on the other hand, the principal veins strike northeast and southwest parallel to joint fractures. In any pit or series of pits there is usually a single main vein or several parallel veins following one of these directions of fracturing, and

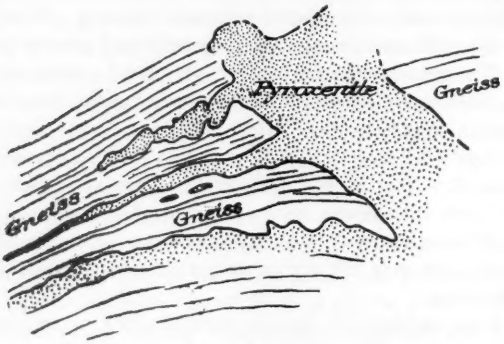
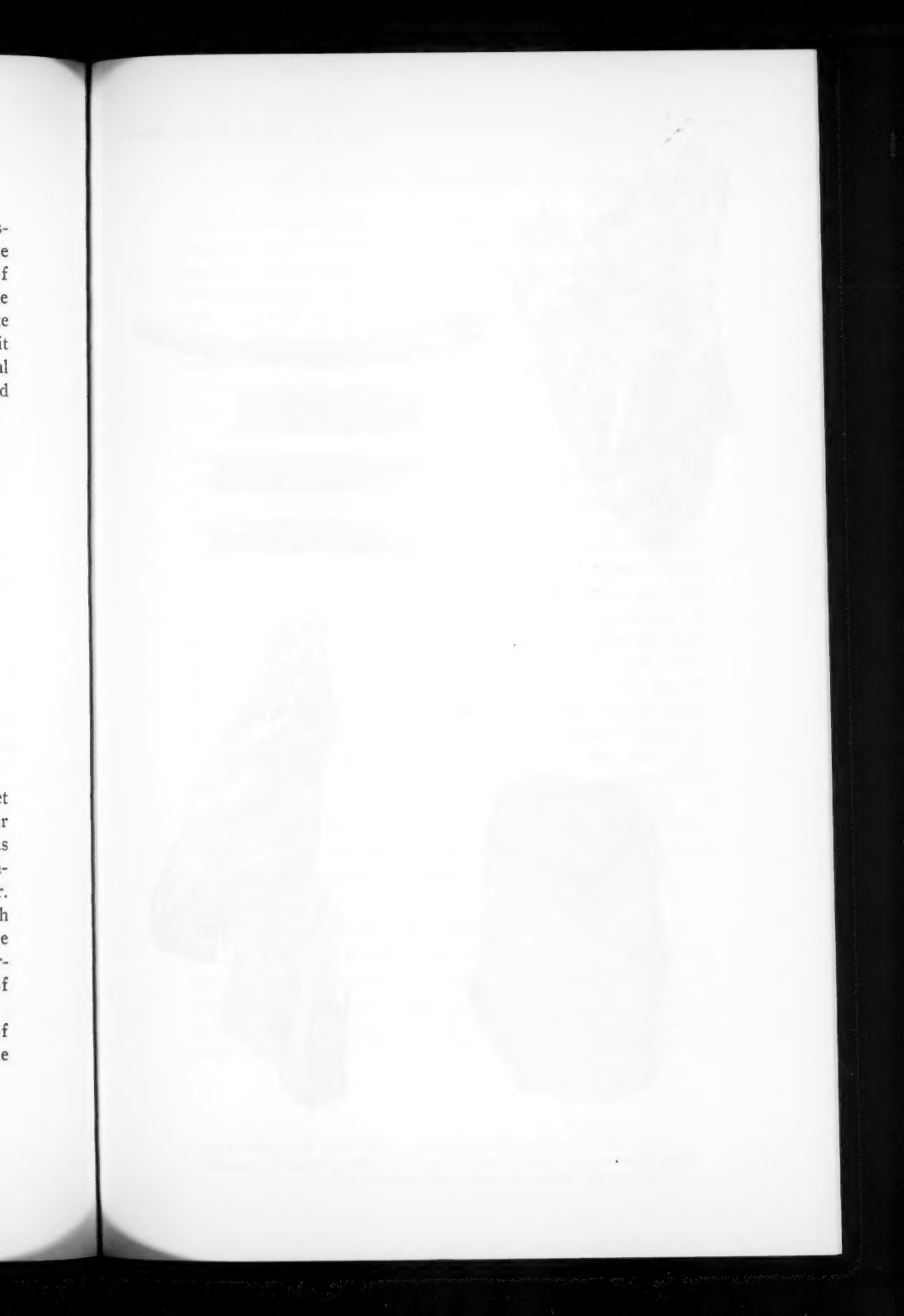


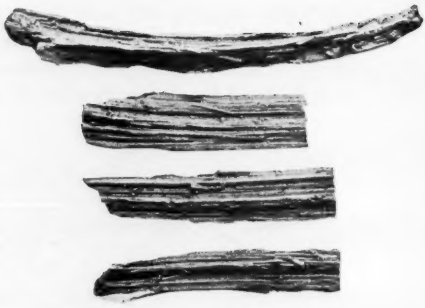
FIG. 62. Pyroxenite intrusive in gneiss at Ella, Ceylon. (After Coomaraswamy.)

sending off minor veins or stringers along the less prominent set of fractures. In some cases the extent of the veins along their trend is so slight that they may be more correctly described as lenses. In other cases a vein of considerable width may contract to a mere seam only to widen again when followed further. The width of the veins varies from less than an eighth of an inch to several feet, and some as narrow as two or three inches are worked. The walls are usually sharply defined and the bordering rock is not impregnated with graphite to a distance of more than half an inch from the veins.

In small veins the graphite usually forms an aggregate of parallel platy needles set at right angles to the vein wall. In the



b



c

d

a

a, Platy form of graphite from Ceylon; *b*, Platy form of graphite from Dillon, Montana; *c*, Ceylon "needle lump"; *d*, Sharp contact of graphite vein with granite, Dillon, Montana. (All natural size.)

larger veins most of the graphite shows a coarse platy structure such as is shown in Plate II., *a*, though the needle-like structures may be developed in a band from a few millimeters to two or three centimeters across next the walls or next masses of wall rocks enclosed in the vein. The needle-like aggregates are shown in Plate II., *c*. They are in high favor commercially because of their fibrous structure and are known as "needle lump." Spherulitic or radiating aggregates of graphite plates are of occasional occurrence.

Usually the veins consist almost entirely of graphite but other minerals occur in subordinate amounts. Pyrite is almost always present either disseminated between the individual flakes or needles or concentrated in a more or less definite band in the central portion of the vein. Occasionally a pyrite crystal is penetrated by graphite flakes. Quartz commonly milky, usually forms a part of the vein and sometimes occurs as a central band. In a few cases rosettes of graphite flakes occur in the quartz, and in other cases quartz grains lie between flakes of graphite. Although quartz and pyrite are the only accessory minerals which are nearly always present occasional minerals are biotite, orthoclase feldspar, pyroxene (usually augite), apatite, allanite and rutile; the latter is sometimes developed along the cleavage planes in the graphite crystals. In one mine a remarkable cavity or "vug" was encountered which was about 15 feet high, more than a yard wide and oval in sections. Its walls were lined with flaky graphite and similar material filled its lower portion. In some of the graphite veins slight movements subsequent to their formation have bent the graphite flakes or crushed them to an earthy mass and developed slickensided fracture surfaces.

GRAPHITE MINING AND PREPARATION FOR MARKET.

The graphite is mined either from open pits or through vertical shafts connecting with underground workings. The majority of mines are not deeper than 100 feet, though a few go as deep as 400 or 500 feet. On account of the heavy rainfall water is one of the chief obstacles in deep mining. In a few

mines steam pumps and hoists are employed but as a rule the mining methods are still very crude, the acme of mechanical ingenuity being reached in a windlass operated by 5 or 6 men for hoisting the graphite in a sort of tub. The workmen usually ascend and descend by means of rough wooden ladders, tied with jungle ropes and rendered exceedingly slippery by the graphite dust and water. Fig. 62 shows one of the mines of the Kurunegale dis-

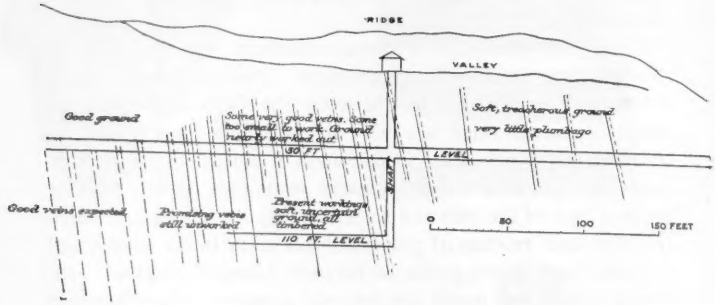


FIG. 63. Section of the Laxapana graphite mine, Maskeliya district. (Ceylon Administrative Reports, 1906.)

trict which, unlike most, has been developed in a comparatively modern manner. The veins at this property follow joint-planes in the gneisses.

The mineral as it comes from the pits may contain as much as 50 per cent. of impurities mostly in the form of quartz and wall rock. It is conveyed in bags to a dressing shed where it is picked over and the impurities reduced to 5 or 10 per cent. It is then packed in barrels for transportation to Colombo or Galle. At these ports it is unpacked and submitted to further treatment known as "curing." The graphite merchants have fenced yards or "compounds" for the final preparation of the graphite for the market. In the methods of "curing" there is some diversity, but the first step is usually to set aside the large lumps and to pass the remainder through stationary screens of several different sizes of mesh. The large lumps and the screened pieces

are then broken with small hatchets by Sinhalese women to remove the coarser impurities such as quartz and are then rubbed up by hand on a piece of wet burlap and finally on a piece of screening to give them a polish. Finally, various grades coming from different mines or differing in size or texture are blended to meet the requirements of various purchasers, a process requiring skill and long experience.

The poorer material is usually beaten to a powder with wooden mauls or clubs, and then sorted into different grades. In some establishments the more impure grades are washed in a tub or pit. In this process the mineral is placed in saucer-shaped baskets and by a circular "panning" motion while immersed in the water the graphite particles are thrown off into the pit while the heavier impurities, especially pyrite, remain behind. To separate the very fine material the powdered graphite is placed in a basket with somewhat the shape of a large dust-pan. When the contents of the basket is thrown into the air the heavier particles fall back into the basket while the finer material is blown forward and falls on the floor.

USES AND PRICES.

The graphite imported into the United States from Ceylon is used mainly for making crucibles and other refractory products. For this purpose it takes preference over any other graphite, on account of its comparatively tough flaky or fibrous character, which contributes to the tensile strength of the crucible. It is used to some extent for lubricating, and in stove polishes. For pencils, amorphous graphite is the principal variety used but some finely ground Ceylon graphite is sometimes added to increase the smoothness of the "lead."

The Ceylon graphite is graded according to fineness as "large lump," "ordinary lump," "chip," "dust," and "flying dust."

The prices paid for Ceylon graphite in New York in 1911 were about as follows:

PRICES OF CEYLON GRAPHITE AT NEW YORK CITY IN 1911.

Ordinary Lump:	Cents per Pound.
Best	8¼ to 9
Medium	7 to 8
Poor	6 to 7

Chip:	
Best	5¼ to 5¾
Medium	4 to 5
Poor	3½ to 4
Dust:	
Best	3½ to 4
Medium	2¾ to 3¼
Poor	2 to 2½
Flying Dust:	
Best	3¼ to 3½
Medium	2 to 2½
Poor	1½

ORIGIN OF THE GRAPHITE VEINS

Many and varied theories have been proposed to account for the origin of the Ceylon and similar deposits, but none have proven wholly satisfactory. Our knowledge of them is however sufficiently definite to permit us to rule out certain of these theories. The deposits are not metamorphosed interbedded coal, since they form irregular vein systems often cutting across the foliation of the enclosing rocks; on the other hand it is perfectly clear that the graphite was deposited along irregular fracture-planes. Any theory of origin through lateral secretion from the wall rocks is untenable because of the extreme sharpness of the vein walls and the scarcity or absence of graphite in the wall rocks. The suggestion that they represent fissures filled with asphalt or other carbonaceous material which was later metamorphosed into graphite, is untenable because in Ceylon and in a number of other localities where such veins occur they are themselves younger than any regional metamorphism or igneous intrusion capable of affecting such a change. Thus both in Ceylon and at Dillon, Montana (see later pages), the veins cut sharply through the schists and gneisses and the youngest of the igneous rocks with which they are associated.

It seems necessary to accept the only remaining hypothesis, that of deposition from some sort of a solution penetrating along fracture planes in the rocks. In short, they are true fissure veins. In regard to the origin and nature of such solutions and the temperature and pressure conditions under

which graphite was deposited from them, practically nothing is known, although speculations on the subject have been numerous. Many of these speculations are based upon doubtful analogies between the artificial formation of graphite and its origin in nature. Prominent among these hypotheses are the following: (1) The solutions were mainly carbon vapor which sublimed with the formation of graphite; (2)[1] the solutions contained metallic carbides which decomposed with the formation of graphite; (3)[2] the solutions were rich in hydrocarbons which yielded graphite on decomposition; (4)[3] the solutions carried oxides of carbon and probably also cyanogen compounds; (5) the solutions carried hydrogen and oxides on carbon which reacted with the formation of graphite and water. The relative merits of these various views have been ably discussed by Professor Winchell in a recent article[4] to which the reader is referred for further details.

The fact that geologists have indulged in so many and varied speculations in regard to the origin of the vein deposits of graphite might lead one to infer that the problem is beyond the reach of the more trustworthy methods of field observation and laboratory experiment. In the writer's opinion this is not true. Field studies of the Ceylon deposits and graphite vein deposits elsewhere[5] have already proven suggestive by showing that the veins are associated with phenomena of igneous (or contact) metamorphism and may themselves have been formed during the last stages of such metamorphism. Although the veins cut the associated igneous rocks and contact metamorphic rocks they carry occasional crystals of the same minerals which characterize

[1] Moissan, H., "Étude du graphite étrait d'une pegmatite," *Comptes Rendus,* Vol. 121, p. 538, 1895.

[2] Hunt, T. Sterry, "Geology of Canada," 1866, p. 222. Cirkel, Fritz, "Graphite," Mines Branch, Ottawa, 1907, p. 89. Walther, J., *Zeitschr. der Deutsch. Geol. Gessell.,* Vol. XLI., pp. 359–364, 1889.

[3] Weinschenck, E., "Abb. der K. bayer. Akad. der Wiss., Vol. 21, part II, 1901, p. 281.

[4] Winchell, A. N., ECONOMIC GEOLOGY, Vol. VI., 1911, pp. 220–230.

[5] Bastin, E. S., "Origin of Certain Adirondack Graphite Deposits," ECONOMIC GEOLOGY, Vol. V, 1910, pp. 143–155.

the contact metamorphic rocks and the contact rocks themselves are often highly graphitic. A genetic connection between the veins and the contact metamorphic phenomena is therefore highly probable. More detailed field study of the Ceylon deposits and of the little known vein deposits of Buckingham, Quebec, should throw much light on this important point.

The most important clues to the origin of the graphite veins will probably be furnished by a study of the other minerals which occur in small amounts in the veins. The relations of some of these minerals to the graphite show that they are contemporaneous crystallizations but closer studies of their exact mode of association are needed in most cases. Something is now known of the stability ranges of two of the most abundant accessory minerals in the Ceylon veins, quartz[1] and pyrite[2] and laboratory experimentation is likely soon to add greatly to our knowledge along these lines. By an application of the Wright and Larsen criteria the writer has already shown that quartz intercrystallized with graphite in a contact metamorphic zone was formed at temperatures below 575° C. and similar tests could probably be applied to the quartz of graphite veins.

In conclusion, no theory of the origin of graphite veins can be satisfactory unless it takes into account not only the graphite but the accessory minerals, quartz, pyrite, and numerous silicates which are commonly present in these veins. Their presence imposes certain limitations which must be reckoned with.

LITERATURE ON CEYLON GRAPHITE.

Much of the information which has been published in regard to the graphite deposits of Ceylon is in the form of careful mineralogical descriptions of Ceylon minerals in European Museums. Nos. 9, 15, and 19 of the bibliography are the most important papers of this character.

For direct field observations the excellent writings of A. K.

[1] Wright, F. E., and Larsen, E. S., "Quartz as a Geologic Thermometer," *American Jour. Sci.*, Vol. 27, 1909, p. 421.

[2] Allen, E. T., "Sulphides of Iron and Their Genesis," *Amer. Jour. Sci.*, Vol. XXXIII, pp. 169-236, 1912.

Coomaraswamy for several years in charge of the Mineralogical Survey of Ceylon, and of his associate, James Parsons, are of first importance (Nos. 1 to 8). Some field data has also been contributed by J. Walther (18).

The best information in regard to the mining of graphite and its preparation for the market has been furnished by G. A. Stonier (16).

Annual figures showing the amount and value of the graphite exported and the countries to which it goes are published in the Ceylon Government Blue Book.

1. Coomaraswamy, A. K. On Ceylon Rocks and Graphite. *Quart. Jour. Geol. Soc.*, London, Vol. LVI, pp. 590 et seq. 1900. A preliminary description of certain rocks and graphite deposits of Ceylon. Material mostly embodied in revised form in later writings by the same author.

2. Coomaraswamy, A. K. The Crystalline Limestones of Ceylon. *Quart. Jour. Geol. Soc.*, Vol. LVIII., pp. 399–422. 1902. 2 plates. Describes the distribution of the crystalline limestones, their accessory minerals, and their contact relationships with the gneisses (granulites).

3. Coomaraswamy, A. K. Wollastonite-Scapolite Gneisses of Ceylon. *Quart. Jour. Geol. Soc.*, Vol. LVIII., pp. 680–689. Map. 1902.

4. Coomaraswamy, A. K. The Crystalline Rocks of Ceylon. "Spolia Zeylanica," Ceylon. Vol. I., Part IV., Feb. 1904. (8 pages.) A brief account of the crystalline rocks of Ceylon. Includes no mention of graphite deposits.

5. Coomaraswamy, A. K. The Balangoda Group. *Geol. Mag.*, Decade V., Vol. I., pp. 418–422. 1904. Describes occurrences of granite and related pegmatite in Ceylon.

6. Coomaraswamy, A. K. Intrusive Pyroxenites, Mica-pyroxenites, and Mica Rocks in the Charnockite Series or Granulites in Ceylon. *Geol. Mag.*, Decade V., Vol. II., pp. 363–369. 1905.

7. Coomaraswamy, A. K. The Rocks and Minerals of Ceylon. Guide to the Collections of the Colombo Museum. 1905. Devotes 2 pages to the graphite deposits of Ceylon.

8. Coomaraswamy, A. K. and Parsons, James. Ceylon Administration Reports: Mineralogical Survey.

1903. Pp. L 6–8. Describes methods of working the graphite mines and details of several properties.

1905. Pp. E 2–4. Describes the mode of occurrence of

graphite in Ceylon, discusses its origin, and briefly describes a number of properties. 4 figures.

1906. P. E 5. Description and maps of graphite mines near Laxapana. Bibliography of Ceylon geology.

1908. Devotes one half page to the distribution of graphite in Ceylon and gives brief notes on some mines in the Kurunegale district.

9. DIERSCHE, MAX. Beitrag zur kenntniss der gesteine und graphitvorkomnisse Ceylons. *Jahrbuch d. K. K. geol. Reichsanstatt*, Bd. XLVIII., p. 231. 1898. Presents the results of detailed studies of geological and mineralogical data and specimens collected in Ceylon in 1894 by Prof. Fritz Zirkel. Describes the graphite of the Ragedara district and its mode of association with other minerals, and rock fragments included in the veins. Discusses origin briefly.

10. DONATH, E. Der Graphit. Leipsig. 1904.

11. FERGUSON, A. M. Plumbago. *Jour. Ceylon Branch Royal Asiatic Society*, Vol. IX., Part. II., No. 31, pp. 171–266. 1885. An account of the development of the graphite industry in Ceylon and of the uses of graphite. Statistics of production 1834–1884.

12. FERGUSON, A. M. and J. Ceylon Handbook and Directory. Colombo and London. Pp. xlviii–l. 1908–9. Describes briefly the graphite (plumbago) industry of Ceylon and gives figures of production.

13. GRUNLING, F. Über die Mineralvorkommen von Ceylon. *Zeit. für Kryst.*, Bd. XXXIII., pp. 220–229. 1900. Describes the distribution, mode of occurrence, and mineral associations of graphite in Ceylon.

14. LAUNAY, L. DE. Notes sur la Théorie des Gites Minéraux. (1) La Geologie du Graphite. *Annal des Mines*, 10th Series, Vol. 3, pp. 63–68. 1903.

15. SANDBERGER, F. VON. Beitrage zur Kenntniss des Graphits von Ceylon und seiner Begleiter. *Neues Jahrb.*, pp. 12–16. 1887. Describes geological and mineralogical collections made in Ceylon by B. & C. F. Sarasin.

16. STONIER, G. A. Graphite mining in Ceylon and India. *Trans. Institution of Mining Engineers.* London. Vol. XXVII., pp. 536–545. 1903–4. Describes the methods of mining graphite and preparing it for the market. Eight half-tone illustrations, table of Ceylon production 1834–1902, and map of Ceylon showing location of mines.

17. TENNENT, SIR J. E. Ceylon. London. 5th edition. 1860.

18. WALTHER, J. Uber Graphitgänge im zersetzten Gneiss von Ceylon.

Zeit. der. Deutsch. Geol. Gesell., Vol. XLI., pp. 359–364. 1889. Translated into English in *Records Geol. Survey India.* Vol. XXIV., pp. 42–45. 1891. Contains a description of one of the Ceylon mines and a discussion of the origin of the graphite.

19. WEINSCHENK, E. Die Graphitlagerstätten der Insel Ceylon. Abhandl. der K. bayer. Akad. Wiss., Vol. XXI., Part II., pp. 281. et seq. 1901.

20. WEINSCHENK, E. Memoire sur l'histoire Géologique du Graphite. Congrés Géologique International, *Comptes Rendus,* Paris, 1900. Pp. 447–457. Pp. 449. Summarizes the essential characteristics of the graphite deposits of Ceylon and important deposits elsewhere and emphasizes their diversity in origin.

VEIN-DEPOSITS OF GRAPHITE NEAR DILLON, MONTANA.

The mine of the Crystal Graphite Company, near Dillon, is of more than ordinary interest because in its geological relations and in the character of its graphite it shows many similarities to the famous deposits of Ceylon. Unfortunately the quantity of high-grade graphite yet discovered is too small to form the basis of an industry like that of Ceylon, but there seems good prospect of the development of one paying mine.

The principal workings on the property are located about 9 miles southeast of Dillon (16 miles by wagon road), at the south end of the Ruby Range. They occupy what is known as Crown Point at an elevation of 9,000 feet. The property is within the area of the Dillon topographic map sheet of the U. S. Geological Survey. A good wagon road leads to the mine cabins within a mile of the mine, but from there the steep mountains must be climbed on foot. Without great expense, a wagon road could be constructed to the mine or the graphite transported on pack animals over the steeper part of the trail. The mine is located on the ridge between Timber and Van Camp gulches. According to Winchell[1] the rocks exposed in the Ruby ranges are chiefly the thick limestone series of the Paleozoic series in Montana. The rocks immediately associated with the graphite deposits are limestones and quartzites apparently of this Paleozoic series and underlying quartz schists and slates which are prob-

[1] ECONOMIC GEOLOGY, Vol. VI., pp. 218, 1911.

ably pre-Cambrian. All are intruded by granite and pegmatite and certain other rocks of contact metamorphic origin are developed as a result of this intrusion.

The main workings which are those of economic interest will first be described, then neighboring occurrences of little commercial importance but of much scientific interest.

THE MAIN WORKINGS.

The location of the main or Crown Point workings has already been given. They consist of a number of drifts and crosscuts shown in Fig. 64 below. The graphite veins are shown by solid black lines. The outcrops in the immediate vicinity of these workings are of metamorphosed sedimentary rocks (garnetiferous mica schists, quartz schists, and hornblendic quartz schists), which are intruded by granitic igneous rocks (aplitic granite and pegmatite). With these are associated minor amounts of lime-silicate rocks, evidently of contact metamorphic origin, which consist of quartz, garnet, and pyroxene, the latter often in large crystals. Graphite occurs at one point or another in all of these rocks. The strike of the rocks near the Crown Point tunnel is variable, from N. 5° E. to N. 60° E. with northwesterly dips of 30 to 60 degrees and there are numerous evidences of minor faulting.

Underground Workings.—The first 160 feet of the tunnel may be regarded as crosscut but the workings beyond follow in part graphite veins. The wall rocks where exposed are pegmatite, quartz schist, and garnetiferous mica schist. As shown in Fig. 64 the first 160 feet of the tunnel encounters several small graphite veins, but the maximum width of graphite exposed in any of them is only 2 inches so that they are not workable. The noteworthy feature of this part of the tunnel is the fault-plane shown on the map by a broken line. This was formed after the graphite for it cuts the graphite veinlets. It carries much gouge but no graphite except a little which has been dragged out from the veins. At 160 feet from the portal one of the main graphite veins of the mine is encountered and is followed

by the tunnel for 30 feet to a point where it turns sharply west. This vein is commonly vertical but where it turns the dip shifts to 60° north. In places it shows 4 inches of very pure graphite, and in one place the graphite is reported to have been 6 inches wide. Beyond the turn this vein merges with the main vein of the mine which is developed by the 120-foot northeast to southwest drift shown on the map.

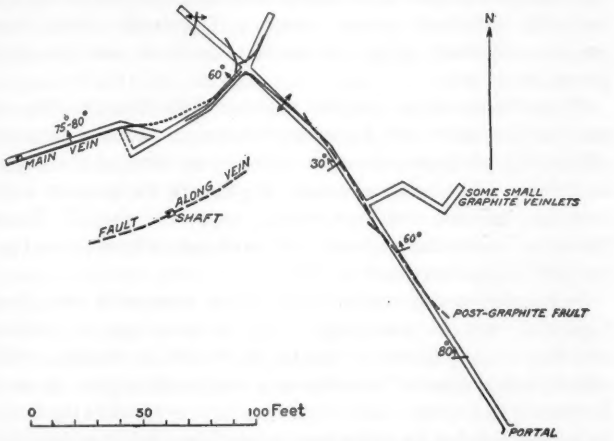


FIG. 64. Plan of underground workings at graphite mine near Dillon, Mont.

The main vein shows from 2 to 8 inches of very pure graphite. It dips from 60° to 80° north. Near the main tunnel where it shows 4 inches of pure graphite it is in sharp contact with walls of granite-pegmatite, which near the vein contain scattered graphite flakes up to ¼ inch in size. The graphite has been fractured by post-mineral movements along the vein and slickensides are developed in both the graphite and the wall rock.

One of the best exposures in the mine is 10 feet from the face of the main tunnel where a graphite vein is shown in cross section. The wall rock here is altered quartz schist, in places becoming micaceous, and is traversed by a nearly vertical fracture

zone along which graphite has been deposited. The vein is about 2 feet wide and consists of an irregular network of graphite veinlets enclosing many sharp-walled schist fragments. The graphite forms about half of the vein material and the veinlets locally unite to form irregular bunches. The south wall is fairly regular, but the north wall is ragged and is penetrated by irregular apophyses from the main graphite mass. Included minerals such as quartz and pyrite were not observed in the Dillon veins although careful search will probably reveal their presence especially when the surface oxidized zone has been passed.

The structure of the graphite is rather difficult to describe and may best be understood from the photographs opposite page 427 (Plate II.) which also show its similarity to some of the Ceylon material. When broken between the fingers the graphite separates into splinters which are roughly spear-head shaped. Truly fibrous or needle-like varieties such as occasionally occur in Ceylon (Pl. II., *c*) also occur at Dillon.

In comparing the graphite from these veins with that from Ceylon it must be remembered that the workings are shallow and that surface alteration has produced certain changes which will be less noticeable when greater depths have been reached. For example, (1) the luster of this graphite, even when the lumps have been polished or rubbed up, is much less brilliant than that of much of the Ceylon material; (2) thin films of iron oxide occur along parting planes between some of the graphite plates; and (3) the graphite is softer than most Ceylon graphite and grinds up more readily though still yielding a flaky product. These differences will decrease with depth but the product will probably never be entirely similar to that from Ceylon. In spite of these differences the Dillon graphite is undoubtedly suited for crucible making and with steady production a market for such purposes might be built up. For lubricating purposes the material should be excellent. The absence of the cheap labor available in Ceylon for sorting and cleaning is a handicap which may in a measure be offset by intelligent and expeditious methods of mining.

Although the vein deposits described above are the only ones of economic promise in the vicinity, graphite occurs in a number of other ways which are of interest because of the light they throw upon the conditions under which the mineral was formed.

Graphite in Granitic Rocks.—In small open pits near the main mine there are good exposures of graphite-bearing granite and granite pegmatite and similar occurrences were noted in neighboring prospects. These rocks are made up of quartz and orthoclase feldspar, usually with minor amounts of biotite. In the granites garnet is usually abundant, and graphite may occur intercrystallized with the quartz, feldspar, and other minerals or as small, sharp-walled veinlets. When intercrystallized the graphite is usually not evenly distributed, but is most abundant along the border of the granitic masses or along certain planes within them which resemble planes of magmatic flowage rather than of shearing.

Where pegmatite has been intruded parallel to the foliation of pelite schist in such a manner as to form an injection gneiss the graphite is confined mainly in the pegmatite in which it forms fibers sometimes an inch long lying parallel to the foliation. (Faithful claim.) Where the granitic rocks intrude crystalline limestone the graphite is also confined mainly to the igneous rock. One pegmatite dike 2 to 3 inches wide traversing limestone (Faithful claim) is nearly half graphite, the flakes lying parallel to the plane of the dike and terminating abruptly at the limestone contact. At another place (Faithful claim) pegmatite which is in sharp contact with limestone becomes nearly half graphite in a zone ½ to 1 inch wide next the limestone. The graphite flakes here are up to ¼ inch across and some of the graphite aggregates are ¾ of an inch across. Scattered flakes of graphite, usually under 3 millimeters, occur in the pegmatite away from the contact and the limestone also contains scattered flakes of graphite usually under 1 millimeter and some small pyroxene grains even at a distance of a foot from the pegmatite. At another place (prospects on north side of Timber Gulch, about 1 mile east of main workings) a 4-foot sill of pegmatitic granite shows graphite rather evenly distributed through it in nests or

irregular aggregates whose plates interlock with the quartz and feldspar crystals of the rock. The bordering limestone contains only occasional flakes of graphite and one veinlet of graphite 1½ inches wide which traverses the granite terminates abruptly when it reaches the limestone.

Graphite veinlets traversing the granitic rocks are usually sharp-walled as shown in Pl. *II., d,* and they occasionally penetrate the cleavage cracks of large feldspar crystals. Microscopic examination of the immediate contact between graphite veinlet and granite in the vein shown in Plate II., *d,* failed to show any metasomatic alteration in the granite as a result of the formation of the graphite vein. In a zone about ⅛ of an inch wide along the exact contact flakes of graphite showing no regularity of orientation are intergrown with quartz and microcline feldspar. Usually the graphite plates lie between individual quartz or feldspar crystals, but occasionally the graphite plates cut across single feldspar crystals apparently without reference to the planes of crystal cleavage. The microcline is usually beautifully fresh and the slight alteration occasionally observed appears to bear no relation to the graphite, but to be due to slight surface weathering. Minute grains of quartz and fresh microcline are common within the main mass of the graphite vein, and the intimate and irregular manner in which they are intergrown with and penetrated by graphite shows that they crystallized contemporaneously with the graphite. At one prospect (tunnel on Bird's Next claim) where garnetiferous granite and pegmatite are intruded parallel to the bedding planes of crystalline limestone and somewhat schistose impure quartzite, the graphite is largely confined to a series of fracture seams in the igneous rocks. Most of these fractures strike north and south and are nearly vertical, and they occur through a zone about 20 feet wide. The width of the graphite veins is usually under ¼ inch, the widest observed being 1 inch. Most of them terminate abruptly when the limestone is reached but in a few places there are small seams of graphite in the limestone while in other places graphite flakes usually under 2 millimeters in size are scattered irregularly through pyroxenic limestone. Some of the crystalline limestone

near these workings is very coarse with single calcite grains 1 inch across.

Where the granite is somewhat foliated (pits near main workings) the graphite veinlets may follow or cut across the planes of foliation. Many of the smaller graphite veins unlike the large ones show the graphite plates elongated parallel to the plane of the vein.

Graphite in Lime-silicate Rocks.—These rocks which are exposed in several pits near the main workings appear to be confined to the contact between granitic rocks and somewhat calcareous schists and they were probably formed through the contact metamorphic effects of the granites. They show pyroxene, garnet and quartz as their principal constituents and in some cases are coarse-grained with quartz lenses and pyroxene crystals several inches across, though in other instances fine-grained and showing remnants of bedding. Some of the lime-silicate rocks pass gradually into a garnetiferous mica schist which is probably a metamorphosed pelitic sediment. The graphite occurs in these rocks partly in isolated plates and scattered irregular aggregates which are intercrystallized with the pyroxene and other minerals, and partly along distinct fractures. Some of the phases of these rocks which show remnants of bedding have been highly brecciated and in the brecciated portions the bedding becomes obscured and there is an unusual abundance of graphite. The graphite in the breccias is mainly confined to fractures and irregular spaces between the rock fragments and forms short vein-like masses usually less than ½ inch wide though locally broadening to 2 inches. Their borders are of extreme sharpness. The individual graphite flakes are commonly under ½ inch in length and are set at high angles to the walls of the fractures. In a few of the veinlets a little white quartz and calcite are intercrystallized with the graphite, usually near the center of the veinlet; thus in one instance a graphite veinlet 1½ inches wide contains a central band of quartz ½ to ¾ of an inch wide. An unusual rock associated in small amounts with the brecciated phases of the lime-silicate rocks consists of an aggregate of orthoclase crystals up to 4 millimeters across with a nearly equal

amount of graphite, the two minerals being associated in such a way as to give rather an evenly mottled appearance in the hand specimens. The graphite plates in this rock are frequently arranged in radiating aggregates.

Graphite in Crystalline Limestone.—At a prospect on the south side of Timber Gulch about 100 feet above the stream level, crystalline limestone has been extremely altered with the development of "augen" up to 6 inches across which are nearly pure feldspar except for an occasional enclosure of graphite. The limestone contains abundant grains of pyroxene and garnet and carries flakes of graphite in greater abundance than any of the limestones observed on these properties.

SUMMARY AND CONCLUSIONS.

The salient features of these observations and the conclusions which may be drawn from them may be summarized as follows:

1. The sedimentary rocks of this locality have been extensively intruded by granitic rocks with resulting contact metamorphism and the development of typical contact metamorphic minerals.

2. The graphite of commercial promise was deposited along irregular fractures which appear to cut the above rock types indiscriminately, with the possible exception of the limestone.

3. With the exception of the larger veins above mentioned, graphite is found principally in the granitic rocks where it occurs both as a contemporaneous crystallization and as a filling of small fractures formed after the rock had become friable but not necessarily cold.

4. Granite walls of the veins showed no metasomatic alterations whatsoever.

5. Graphite was observed disseminated in the sediments only in small amounts and only where these sediments show clear evidence of contact metamorphism by the presence of typical contact metamorphic minerals.

The writer is in complete agreement with Professor Winchell in believing that the present distribution of the graphite is a result of the intrusion of the granitic rocks. The evidence shows conclusively also that some of the carbon which finally crystal-

lized as graphite formed a constituent part of the granite magma. An inquiry into the state in which the carbon existed in the magma, whether as the element carbon or in some compound of carbon, lies of course in the realm of speculation, and the various theories that have been advanced have already been summarized. Although it seems probable that the graphite, especially of the vein deposits, was formed through the decomposition of some compound of carbon, it has not been shown that carbon cannot exist in igneous magmas in the elemental form. The mere fact that graphite volatilizes only at high temperatures under ordinary atmospheric conditions forms no valid argument against its existence in the elemental form in a rock magma at much lower temperatures. It would be as reasonable to say that since quartz is a highly refractory substance under ordinary conditions, it cannot exist in magmas under much lower temperature conditions. We know that it does so exist. In both cases the all important points are the nature of the solvent and the physical conditions in the solution.

In conclusion it should be pointed out that the Dillon deposit is similar in its general geologic features to the deposit at Lead Hill, New York, described by the writer in an earlier number of this journal. At both localities sedimentary rocks have been intruded by granitic igneous rocks with notable contact metamorphic effects and the development of graphite in the contact metamorphic rocks and in both the sedimentary and igneous rocks. In both localities graphite occurs disseminated and also in veins. In both localities graphite veins are sometimes sharply cut off by crystalline limestone showing that some of the limestone was mobile after certain graphite veins had formed.

In the Lead Hill region graphite of earlier dynamo-metamorphic origin is known to occur disseminated through schists in the near vicinity, and furnishes a probable source for the coarser graphite of the contact deposit. In the Dillon region carbonaceous sedimentary beds that would furnish an adequate source for the graphite have not been discovered but the region has been little explored geologically. That the carbon was abstracted by a granitic magma from carbonaceous sediments which it traversed seems the most probable origin.

STUDY OF A CONTACT METAMORPHIC ORE-DEPOSIT.[1] THE DOLORES MINE, AT MATEHUALA, S. L. P., MEXICO.

J. E. Spurr, G. H. Garrey, and Clarence N. Fenner.

SUMMARY.

The Dolores Mine is situated at the east base of a small mountain range, near Matehuala, S. L. P., Mexico, in an arid country. The range is of blue Mesozoic limestone, overlain by shales, which form the valleys on both sides. The range has the structure of a halved dome, with a dip slope on the west, north and south, and an enormous normal fault on the east, which has a minimum displacement (vertical) of 1,500 meters. In the center field of the half dome are two areas of intrusive quartz-monzonite, showing evidence of dawning magmatic differentiation in situ. Near these intrusions are lime-silicate rocks, the product of metamorphism. Around the northern or Cobriza intrusion the lime-silicate rock is abundant and widespread; near the southern or Dolores intrusion it is scantier and never departs far from the igneous rock. These lime-silicate rocks originate by (1) regeneration, (2) addition, (3) replacement or substitution. As the distance from the metamorphic center (or the intrusion) increases, metamorphism by regeneration increases relatively to that by addition and substitution. Near Dolores metamorphism is mainly by addition and substitution. Among the metamorphic minerals a regular sequence obtains: 1, Aluminous pyroxenes; 2, aluminous garnet (grossularite) and vesuvianite; 3, wollastonite; 4, lime-iron pyroxene (hedenbergite); 5, lime-iron garnet (andradite); 6, fluorite, quartz and metallic sulfides (and actinolitic hornblende); 7, metallic sulfides (and quartz and fluorite); 8, calcite. Each of these stages replaced the preceding minerals in part. The fact that these minerals replaced, in their

[1] Published by permission of the American Smelting and Refining Co. and of the Carnegie Geophysical Laboratory at Washington.

regular sequence, limestone, monzonite, and the earlier silicates, shows that the sequence was due to changing solutions whose composition corresponds to that of the successively deposited minerals. The following changes of composition of solutions is therefore shown: *A,* Alumina-silica-lime; *B,* silica-lime; *C,* silica-lime-iron (and other metals); *D,* lime. There is reason to believe that the lime in these solutions may have been absorbed from the limestone, eliminating which, we have: *A,* alumina-silica; *B,* silica; *C,* silica-iron (and other metals). This corresponds perhaps with the alaskite-quartz, quartz magma-solutions which represent the end-product of siliceous magmatic differentiation.

Stages 6 and 7 above are the stages of ore-deposition. This is divisible into substages, as follows: *a* Chalcopyrite and pyrite; *b* arsenopyrite (slightly auriferous); *c* pyrrhotite and pyrite (may or may not be argentiferous); *d* blende; *e* galena. These for the mountain (Dolores mine). In the valley are mines showing strongly the (*b*) *c* (*d*) stage and rich in silver. This valley block has no copper ores; the mountain block has only relatively small and insignificant silver (pyritic) veins. The two blocks are separated by the great fault above described.

The metallic sequence corresponds with the usual one in fissure veins, as outlined by Mr. Spurr in an earlier paper. The conclusion is that the solutions which produce contact metamorphism originate in and spring from the zone of differentiation of igneous magmas, which zone is in the lower part of the zone of crystallization, and differs from the solutions which deposit ordinary fissure veins by the absorption of lime from limestones. Ore-deposition in either case is a magmatic phase, partially independent of temperature. The principal ore-zones, largely dependent on temperature, are defined, with special reference to contact metamorphic deposits.

INTRODUCTORY.

The Dolores mine is situated a few miles from Matehuala, in the state of San Luis Potosi, Mexico, in an isolated diminu-

tive mountain range known as the Sierra del Fraile. The range consists of Mesozoic blue limestone, which has been intruded by quartz-monzonite; and the metamorphism and ore-deposition in the range is connected with these intrusions.

In the Dolores property the intrusive rock occupies a belt about 1,000 m. long, and 300–400 m. wide. Surrounding it, and lying between it and the limestone is a practically continuous belt of lime-silicate rock, plainly of metamorphic origin. Nowhere does this rock pass into the limestone far from the intrusion.

The ore-deposits consist mainly of cupriferous pyrite, and are intimately associated with the lime-silicate rock; and occur largely at the very contact, frequently with limestone as one wall. This cupriferous pyrite has usually a gangue made up largely of pyroxene and garnet.

The ore-deposits, then, seem to be typical contact-metamorphic ore-deposits; moreover, their regularity appears to make them an ideal example.

The study the results of which are here recorded has been prosecuted at intervals during the six years that Mr. Spurr has been directing development work at the Dolores mine. The work began in 1905 when a geological map of the surface above the mine and existing underground workings was made by Mr. Spurr. In 1908 the underground workings were remapped and brought to date by Mr. Spurr and Mr. Garrey. Considerable microscopic work was done by Mr. Spurr on the rocks and ores. In 1909 Mr. Spurr made an examination of the Cobriza mine, a mile to the north. Subsequent to this work the first draft of the present paper was prepared. Rock collections and thin sections were subsequently submitted to the Carnegie Institute at Washington, and in 1910 were the subject of some months' study by Mr. Fenner, with some collaboration by Mr. F. E. Wright. The results of this work corroborated in the main the field conclusions, and shed some important additional light, while certain minor points were left in doubt, as between the field evidence and the evidence available from the specimens collected. In 1911 the areal holdings of the Company having been largely increased, by addition of the Cobriza mine, a new and more detailed

survey of the district was undertaken. An area of 7 square kilometers was carefully mapped, topographically and geologically, on a scale of 1:2,500; and the mine workings of both mines were remapped and brought to date. The geological work occupied about 7 months for a field party in charge of W. H. Grant, and including H. Dewitt Smith and John G. Barry. During three months of this period W. L. Barrows was included in the party; and Mr. Spurr contributed some six weeks of his personal attention.

In the intervals between the periods of special investigation mentioned Mr. Spurr visited the property several times.

During the close of the last field work, the results of the previous field work and the microscopic work were again put into review in the light of all evidence. The paper in its present form was then drafted by Mr. Spurr.

GENERAL GEOLOGY.

The Dolores mine is situated a few miles from Matehuala, in the state of San Luis Potosi, Mexico, at the east base of an isolated mountain, or diminutive range, known as the Sierra del Fraile. This range has a north and south trend, a width from east to west base, of scarcely over a mile, and a length from its south base to where it passes into low hills, of two or three miles.

The region is a semi-arid one, and the types of mountains and valleys are like those characteristic of the arid and semi-arid regions of the Western United States. The spaces between the isolated mountains or mountain groups are occupied by level valleys, which are mainly floored by the material derived from the erosion of the mountains.

Stratified Rocks.—The Sierra del Fraile consists of blue limestone belonging to the same Mesozoic period as is found throughout the northern Mexico plateau. Broadly speaking, throughout this province, a thickness of several thousand feet of blue limestone is overlain by a thickness of several thousand feet of shales and shaly limestones. The section in this district shows a measurable thickness of 750 meters of limestone below the shale contact, and 900 meters of shale above the contact;[1] but neither

[1] Total of 1 mile.

the bottom of the limestone nor the top of the shales are known. Paleontologically, the rocks of the province seem to range from Jurassic through Cretaceous in age. Throughout this province, the shales habitually form the valleys, the limestones the mountains, irrespective of the complicated folding and faulting; so that in general the mountain ranges are the results of differential erosion.

Structure of Mountain Block.—Taken in an east and west section through the smallest dimension of the range, the Sierra del

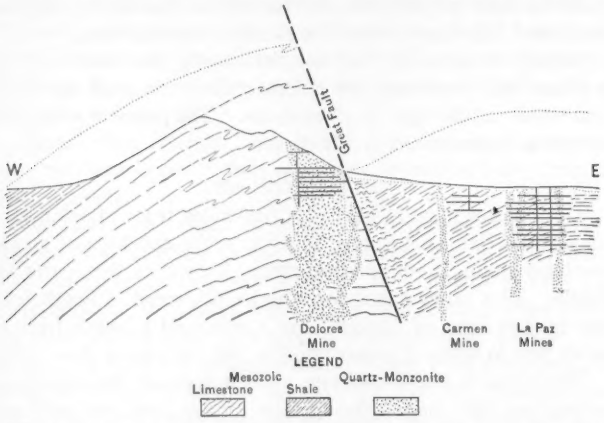


FIG. 65. Vertical cross-section (generalized). Drawn on an east and west line through the Sierra del Fraile. Drawn to scale. Scale 1: 25,000.

Fraile shows essentially a monoclinal structure (Fig. 65). The west side is essentially a dip slope; the east side is determined by an enormous normal fault, which, dipping east at an average angle of probably 70–80°, lies at the very base of the limestone range. This fault has been traced from end to end of the area mapped. The general north-south trend is interrupted by a N. 65° E. course of about 800 meters in length, to the north of which it has been traced a distance of 1,450 meters in a nearly north-south direction; and to the south a distance of 1,700 meters

in a general north-south direction, interrupted only by a N. 60 E. course of 80 meters, parallel to and not far from the 800 meter course. The junctions of the E. N. E. courses with N. S. courses of the fault appear to be angular; the different courses represent parts of the same fault movement, for they do not extend past the junctions. The movement has been a vertical one along the dip, as indicated by striæ.

The monoclinal east-west section of limestone is complicated by folds, usually sharp, with vertical axes that tend to become overthrown to the east, toward the fault. These axes may become overthrown so that they nearly or quite coincide with the general westerly dip of 25 or 30°, in which cases minor thrust faulting commonly has ensued, the upper beds moving relatively to the east and overriding the lower ones. This folding and minor thrust faulting is evidently older than the powerful normal faulting. The general trend of the fold axes is N. W., oblique to the fault, which runs N.-S. The origin of this earlier compression folding and thrust faulting is not at present understood. They may be connected with and contemporaneous with the porphyry intrusions, described later.

The back of the dip slope on the west side of the mountains is the contact with the overlying shales, which thus dip down to occupy the valley to the west; and the same shale series occupies the valley to the east of the Great Fault, abutting against the limestones of the mountain. The base of these shales is not known; but we have here data for a fairly accurate measurement of the *minimum* (total) displacement of the fault only. As a result of carefully worked detailed cross-sections, this minimum displacement is estimated at about 1,500 meters. Apart from this Great Fault, practically no normal faulting has been detected in the range.

The limestone mountain block, taken in a longitudinal direction (N.-S.), shows an anticlinal section (Fig. 66), some three or four miles in length, the limestone beds dipping sharply on the north into the shale-underlain plain, and on the south into low shale hills. The structure of the range, then, is that of a half-

dome, which if completed, would have its longer axis in a north and south direction.

The displacement of the Great Fault as noted above for the central field of the half dome, will probably diminish very rapidly north and south, at both ends of the anticlinal mountain section, till on the north end of the mountain, for example, shale occurs on both sides of the fault, indicating a probable diminution of the displacement of the fault of around a thousand meters. The fault then depends on the domal uplift. Some force has arched up the limestone beds, which broke away from the strata to the east along a somewhat jagged north-south line, so that the elevation was confined to the block on the west.

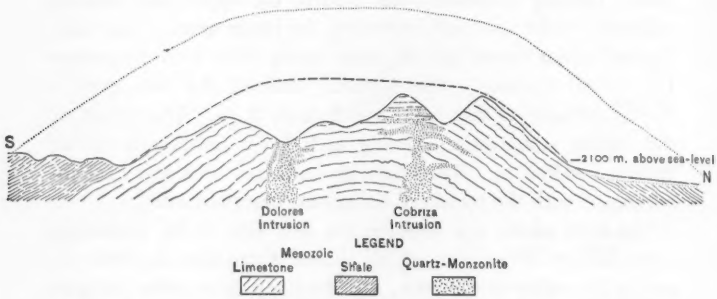


FIG. 66. Longitudinal vertical section (generalized). Drawn on a north and south line through the Sierra del Fraile. Drawn to scale. Scale 1: 50,000.

Intrusive Monzonite.—Occupying the central field of this half-dome are two areas of intrusive quartz-monzonite, lying along a general N.-S. zone, and separated about a kilometer one from another. These intrusions are accompanied by copper mineralization; the northern area comprises the ore-deposits of the Cobriza mine; the southern area that of the Dolores mine. Both are contact-metamorphic deposits of copper.

The Dolores intrusion is in general vertical, cutting across the limestone beds; in part massive, it is also in large part a network of dikes, which in many cases entirely enclose blocks of lime-

stone. This intrusion strikes northwest. On the northwest it dies out; on the southeast it is cut off by the Great Fault. The length is approximately 1,000 m.; the width roughly 300 or 400 m.

The Cobriza intrusion has nowhere the comparative strength of the Dolores intrusion; it consists of a large field of dikes with some irregular larger intrusions; while these intrusions have a strong vertical tendency, many of them have been partially or entirely deflected along the bedding of the limestone, forming sills. This area is irregular, and has a diameter of about a kilometer.

The quartz monzonite intrusions are not confined to the mountain block, although here, so far as known, they are larger. Half a kilometer east of a point at the base of the range, a few hundred meters north of the Dolores mine, an area of shale about half a kilometer in diameter is exposed above the wash; and shows numerous intrusions of quartz monzonite porphyry, the principal one of which is a dike some 30 meters wide, traceable for half a kilometer in a N. 35° E. direction, along a synclinal axis. Associated with these intrusions, but in part cutting across them obliquely, are steeply-dipping silver-bearing pyritic veins in shale, having a general east-west direction. About half a kilometer further east is the mining village of La Paz, where is situated the La Paz and other mines, having a record of an immense production of silver. These all work steeply-dipping nearly east-west veins in shale, near the contacts of quartz monzonite porphyry dikes.

Connection between Intrusion and Structure.—So far as the mountain block is concerned, the localization of the monzonite intrusions in the central field of the half-dome seems to indicate a genetic relation between the intrusion and the structure. This indication is possibly strengthened by some field occurrences in the Cobriza area where the larger intrusive masses have evidently pushed up the limestone strata above them. Nevertheless, the proof is complete, as will be shown later, that the fault originated not only after the intrusion of the porphyry, but after the series of phenomena of metamorphism and ore-deposition

which ensued; that it originated at the very close of the vein-formation and has had its remarkable growth since then. These two lines of evidence may perhaps be satisfied by the explanation that the consolidated intrusive plug of monzonite was subject to subsequent pressure at its base, due to the upward impulse of deeply-buried unconsolidated portions of the magma column. This explanation is the same as was reasoned out by Mr. Spurr in a similar case at Aspen, Colorado. As in the Aspen case, the growth of the dome and fault seem to have been gradual, and probably still slowly progressing.

Age of Intrusion.—These intrusions bear internal physical and chemical evidence, at the Dolores mine, of having consolidated at a considerable depth; they are however younger than at least a certain portion of the Cretaceous.

Age of Faulting.—There is evidence in the sequence of vein-phenomena that the fault originated at the very close of the series of magmatic deposits which followed the monzonite intrusion; therefore its origin may be assigned to the Tertiary. The main movement was accomplished at no very recent date—for since then not only has an immense unknown thickness of shales been stripped from the back of the ridge by erosion, but a measurable triangular prism of underlying limestone besides. The maximum thickness of limestone strata removed (just west of the fault), is 600 to 900 meters; the area of a cross-section of the triangular prism of limestone removed between 300,000 and 400,000 square meters; the migration of the summit of the ridge back (west) from the fault plane about a thousand meters, with a lowering of the summit of the limestone block by about 500 meters average. During that period of erosion the summit of the limestone ridge has been brought down on the average to within about 300 m. of the shale plain; while an area of the limestone block, hardened by unusually extensive contact metamorphism, has resisted so that it remains about 600 meters above the plain (Big Fraile peak), or 300 meters above the average height of the ridge. This actual record of powerful differential erosion proves that the upthrown half-dome of limestone only persists as a topographic mountain on account of its superior hardness to the surrounding shales.

Structure of Valley Block.—The shales east of the fault, so far as mapped, show more numerous and complicated minor folds than the limestones of the range. They are, however, open folds, and not usually compressed; and the general tendency of the dip seems toward the range. Near La Paz, however, there are indications that the summit of this stratigraphic ascent has been reached.

Basalt.—A single narrow vertical dike of olivene basalt in limestone, a few feet wide, has been traced for about 1100 meters, running northwest. It extends southeast to the Great Fault, just beyond which patches of similar basalt are found in place. This basalt is fresh, has no evident relation to the monzonitic intrusions, and is probably later than these intrusions and their subsequent vein-phenomena.

THE QUARTZ-MONZONITE.

Composition and Structure.—The intrusive rock of the limestone block is of varying texture; the thicker portions are granitic, the thinner portions fine-grained and porphyritic. The hand specimen shows feldspar, frequent but not invariable quartz, and, when the rock is fresh, biotite and hornblende. The microscope shows the acessories titanite and apatite.

According to Mr. Fenner's investigations, the phenocrysts show marked zonal structure. The cores are noticeably different from the shells, giving larger extinction angles and possessing higher indices of refraction. There is evidently a normal and uniform variation from a rather basic core to an acid exterior. The average as determined by the Michel-Lèvy and Fouqué methods and by extinction angles on Karlsbad albite twins by Mr. Fenner and Mr. Spurr independently appears to be an andesine, while the outermost shells are quite acid. Both plagioclase and orthoclase appear in the groundmass; but while the lime-soda feldspars form phenocrysts principally, most of the orthoclase is in the groundmass.

Evidence of Magmatic Differentiation.—The composition of the rock exhibits variations throughout (indicating magmatic

differentiation). In several specimens studied the relative amount of orthoclase diminishes till typical granodiorites and even quartz-diorites result. In the other direction, by failure of plagioclase and increase in orthoclase, a granite is produced in one specimen studied. In still another, quartz is lacking; orthoclase is present, and the rock is a monzonite.

The observations of Mr. Fenner as to the internal structure of the rock—that the basic feldspars were first crystallized, and the succeeding feldspar depositions became more and more acid, while the groundmass (of presumably still later deposition) contains most of the orthoclase,—indicate that the process of consolidation was slow, and that during crystallization the residual unsolidified portions of the magma became increasingly acid (siliceous). The variations noted in different parts of the intrusion, between granites and quartz diorites, seem therefore due to the relative local proportion of early and later crystals. The Dolores intrusion[1] then is within the zone of magmatic differentiation in situ, though probably near its upper margin.

CONTACT METAMORPHISM.

Metamorphism of Limestone and Monzonite.—The relation of the lime-silicate rock in the Dolores area is extremely complex, the contacts being obscure and involved. This was at first taken to mean a very irregular form of intrusion, and that the lime-silicate rock was all altered limestone. Subsequent investigations and careful mapping prove that the first supposition was correct, and that much of the complication is thus explained; but prove also the second supposition incorrect, and that much of the lime-silicate rock is altered monzonite. The same was afterwards found to be true of the Cobriza area.

Quantitative Relation of Metamorphic Products to Variations of Sedimentary Rocks.—The outcrops of the Dolores intrusion occupy a markedly lower topographic and stratigraphic position than those of the Cobriza area; while the former may be roughly included in the interval between the 2,100 and 2,400 meter contours, the latter may be roughly included between 2,400 and 2,650

[1] All the specimens studied came from near the Dolores mine.

meters. The former lies in a uniform blue limestone series; the latter approaches the top of the limestone, and the bottom of the great shale series, and occupies in part an horizon where shaly limestone and shale beds alternate with the blue limestone.

Around the Dolores intrusion the lime-silicate rock occupies a narrow and fairly regular fringe, never departing far from the contacts into the limestone. The metamorphism of the Cobriza area, however, extends far laterally along the bedding, and has more or less completely altered all the strata above a general elevation of about 2,400 m. Since the two intrusive areas are identical in composition, age and nature of associated lime-silicate rocks, the noted differences must be due to the differing character of the metamorphosed sedimentary rocks.

Methods of Metamorphism.—There are at least three possible methods of origin for these lime-silicates: (1) the constituents may have existed in the rocks and simply have been recrystallized into lime-silicates at the elevated temperature produced by the intrusion, and under the influence of fluid "crystallizing agents" circulating at that period; (2) by the combination of materials already in the rock with materials brought in solution, at or near the intrusive period; (3) by the replacement of existing rock material by most or all of the materials of the lime-silicates, at the same period. All these processes are illustrated in this district, and may be designated: (1) *Metamorphism by regeneration;* (2) *Metamorphism by addition;* (3) *Metamorphism by replacement* (or *substitution*).[1] An observed variation of No. 1, where the migration of one material to unite with another has been not more than a few inches, may be called *Metamorphism by reaction.*

Types of Metamorphism in the Cobriza Area.—The south margin of the Cobriza area alteration is marked by the metamor-

[1] Dr. F. E. Wright correctly calls attention to the fact that the process of "Metamorphism by Addition" involves a partial removal of the original material, as well as the contribution of foreign material, and hence that the process involves replacement, differing from the third process in that in the latter the materials forming the lime-silicates are typically all of foreign origin. It is in this sense that the terms are defined; and it should be understood that between the three processes there is a continuous series.

phism of shale bands to hornstone[1] containing disseminated pyrite, and small crystals of white grossularite garnet. These alternate with unaltered blue limestone bands and begin at a distance of 400 meters from the nearest intrusion, which is not large. This is apparently mainly metamorphism by regeneration. Proceeding toward the intrusions, it is found that not only the shale beds but the shaly limestone beds become metamorphosed to hornstone spotted with pale green to greenish white grossularite garnet. Since the blue limestone here still remains unaltered, it is evident that metamorphism by regeneration must account for the metamorphism of the shaly limestone bands; but to account for the fact that these shaly limestone bands are metamorphosed here, and not altered further away from the intrusion, where the shale beds are metamorphosed, we must also allow that there has been metamorphism by addition. Still nearer the center of metamorphism the blue limestone beds become gradually entirely replaced by massive red garnet (grossularite). The latter is plainly the result of metamorphism by addition, or even by total replacement. The alteration takes place not only along bedding planes in the limestone, but equally readily along transverse fractures, replacing the limestone from these circulation channels till the whole rock is replaced. The law may be deduced for this Cobriza area that as the distance from the metamorphic center (or the intrusion) increases, metamorphism by regeneration increases relatively to metamorphism by addition and total replacement; and with increasing proximity to the intrusive center the reverse obtains.

Types of Metamorphism in the Dolores Area.—The stratigraphically lower limestones which surround the Dolores intrusion are similar as a mass to the purer bands of blue limestone noted above as metamorphosed only in relative proximity to the intrusive field. Here, accordingly, the metamorphism of the limestone is invariably found not to exist many meters from the

[1] Microscopic study of a typical specimen (G 52) of this hornstone, by Dr. F. E. Wright, showed it to be too fine for satisfactory determination. The rock contains abundant calcite and some cryptocrystalline quartz. There is also a considerable quantity of a mineral which may possibly be prehnite; and patches of probable zoisite.

outside contacts of the intrusive mass and is relatively regular; and according to the Cobriza law this altered limestone is due almost entirely to metamorphism by addition or by total replacement. The hornstones and the accompanying white to greenish small grossularite garnets, characteristic of the chiefly regenerated silicate rocks of the Cobriza area, have not been observed in the Dolores area.

Preponderant Importance of Metamorphism by Substitution. Both in the Dolores and the Cobriza areas the monzonite has been extensively, and locally intensely, metamorphosed, the lime-silicates produced being identical with those resulting from the alteration of limestone, though not, on the whole, in the same relative proportion. For example, massive red garnet (grossularite) has been formed at the expense of limestone and monzonite alike. This proves such an enormous preponderance of material brought in by the metamorphosing solutions that the process becomes metamorphism by substitution.[1] There are, however, exhibited all stages between metamorphism by total substitution and metamorphism by addition, the former indicating the more intense activity.

The relative amount of metamorphism of limestone and monzonite varies greatly in different localities. Usually both the limestone and the monzonite have been highly altered for a broad band on either side of a contact. In other cases the monzonite comes up to the limestone contact with little alteration. In still other cases, the monzonite has been considerably altered, but the blue unaltered limestone comes up almost or locally quite to the contact.

Sequence of Metamorphic Minerals.—Among the minerals produced by metamorphism a striking and regular sequence has been observed, especially noticeable near the intrusive center, where the metamorphic action has been more intense.

Pale-green Aluminous Pyroxene.—The first result of metamorphism was a very pale green pyroxene. This develops in immense amounts in the monzonite, and to a much less extent in

[1] These conclusions correspond with those reached at Velardeña. ECONOMIC GEOLOGY, Vol. 3, No. 8, 1908, p. 711.

the limestone. Numberless observations show that the metamorphosing solutions have penetrated the monzonite along fractures, and have metamorphosed the adjacent rock. These pale-greenish bands, in many of which the nature of the original rock is still discernible, as, for example, in the survival of the unreplaced quartzes, have an anastomosing vein-like form in the early stages, with monzonite between showing even its dark minerals intact; in the later stages the rock is entirely replaced, and with difficulty recognizable.

Mr. Fenner observes:

"In a number of the comparatively unaltered igneous types there is some development of secondary products. A granular pale-green pyroxene frequently occurs, in places closely associated with former biotite and hornblende areas, and in others developed entirely at random. . . . No. 10 is of especial interest. The slide shows that the original rock was a monzonite, but throughout the feldspar areas much green pyroxene in granules or small crystals has been developed, while the feldspars are still very fresh-looking. The quantity of pyroxene is so large that a development from previously existing femic constituents alone does not appear probable, and the introduction of foreign material must be assumed. There is no trace, however, of channels by which this has been accomplished, and it must be referred to a saturation of the rock through capillary or subcapillary spaces. The solutions appear to have gained access even to the interior of feldspar fenocrysts. . . . It is evident that within a short distance an almost unaltered igneous rock passes into one which is composed essentially of metamorphic minerals. Most of the thin sections show rocks which are either almost unaltered or have been completely replaced by secondary aggregates."

Pale Red-brown Grossularite Garnet.—The pale-green pyroxene stage is succeeded by abundant garnet, appearing usually as massive bands in the hand specimen, with little trace of crystallographic outline, and of a characteristic pale red-brown color, which locally varies to a yellow brown or rarely to a greenish tinge. These colors correspond with grossularite. This garnet cuts the earlier pale-green pyroxene rock in definite veins. In a single block (Fig. 67) the apparently fresh monzonite may be seen cut by the pale green pyroxene veins or bands (formed by replacement) and both by the reddish garnet bands. These bands

are also entirely due to replacement proceeding outward from fractures. In other localities (Gonzales lower tunnel) a complete replacement of the pale-green pyroxene rock by the red garnet rock is observable, irregular residual areas of the pyroxene rock remaining.

This reddish massive grossularite has replaced the monzonite and the limestone in about equal amount, and with the same facility—although perhaps it shows a certain preference for the limestone. In the Carmen tunnel of the Cobriza mine the change

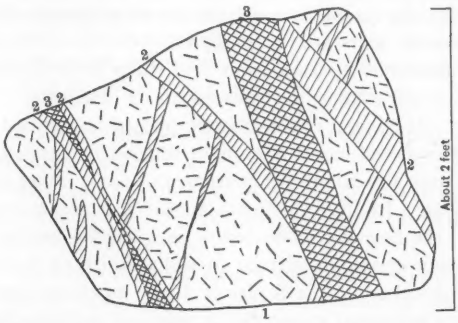


FIG. 67. Sketch of block of monzonite from Carmen tunnel. Showing (1) fresh-appearing quartz-monzonite (specimen 60—see analysis); (2) very pale-green pyroxene rock, produced by alteration of monzonite from fractures (specimen 59—see analysis); (3) red grossularite garnet and vesuvianite, cutting across and splitting open No. 2 veins, and also formed by replacement of monzonite, in part at least.

from unaltered blue limestone as the intrusive is neared is well shown. The limestone seems here of uniform composition. As the intrusion is approached, the garnet-forming solutions have penetrated along bedding-planes, and have replaced the limestone on each side, so that alternate bands of red garnet and blue limestone result. All doubt as to this being a true metamorphism by addition or even total substitution is removed by occasional veins of garnet which have formed along fractures transverse to the bedding.

Contemporaneous with the red-brown garnet was the crystallization of vesuvianite, which is always observed as sheafs of radiating crystals. Though frequent, the amount of vesuvianite formed is slight, and will not amount to one-thousandth part of the volume of the contemporaneous garnet. So far as observed, the vesuvianite has been formed only by alteration of the monzonite, and is characteristic of an intensely metamorphosed band, generally close to the limestone contact.

Wollastonite.—Distinctly subsequent to the reddish garnet stage was the formation in great quantity of wollastonite. The wollastonite always has a very fibrous development, though in many cases the fibers are microscopic.

The wollastonite appears from field study to be formed preferentially as a metamorphic replacement of limestone. The proportion of this mineral in the metamorphosed limestone to that in the metamorphosed monzonite might roughly be expressed as 10 to 1. Its most important origin seems to be as a direct alteration of limestone. In the occurrence in the Carmen tunnel above described, the blue limestone layers between the reddish garnet bands become gradually altered to wollastonite as the intrusive field is approached. This is plainly a case of metamorphism by addition. Occasional cross-cutting veins of wollastonite, intersecting the red garnet, show here again that the presence of the wollastonite in certain bands only has no connection with the original composition of these particular layers of limestone as contrasted with the others. Silica of foreign origin has been added to the original limestone to form by combination the new mineral. Similarly, on the hill near the Dolores mine, a solid nearly perpendicular vein of wollastonite some 3 feet thick was noted cutting squarely across the stratification of unaltered blue limestone. The vein was localized along a slight normal fault, and had replaced the limestone in the crushed zone. The wollastonite is sprinkled with small yellow-brown garnets belonging to the preceding stage of deposition. They are here quantitatively insignificant but appear contemporaneous with the wollastonite. This indicates that the change in the character of the magmatic solutions was a gradual one.

The wollastonite has replaced the pale-green pyroxene of the first stage of silicate deposition with considerable facility, but the reddish garnet has been relatively resistant, although it has been attacked. Rocks made up of this pyroxene with red garnet bands or veinlets have sometimes had the pyroxene replaced by wollastonite—with the result that at first sight the garnet seems later than the wollastonite mass.

Mr. Fenner observes:

> "Probably wollastonite is the most usual mineral by which pyroxene is replaced. . . . In No. 58 the wollastonite has spread out in an irregular network through pyroxene and in places merely small scattered grains or irregular patches are left in the wollastonite. In Nos. 14 and 15, similar effects are observable, and in No. 43 the substitution has proceeded so far that only an occasional grain of pyroxene is left."

Some of the specimens mentioned are metamorphosed monzonite, some metamorphosed limestone.

The wollastonite cuts in veins across the more resistant earlier minerals, showing that the solutions which deposited it bore all of its constituents in solution.

The chert bands in limestone are altered to wollastonite, from the margins inward. This was even noted near the Dolores mine at a point sufficiently far from the intrusion that no other metamorphism was noticed. The narrow vein of wollastonite forming in the chert next the limestone here seems to represent metamorphism by reaction—a variation of metamorphism by regeneration, as above stated. Here then, as in the Cobriza area, the ratio of metamorphism by addition and replacement to metamorphism by regeneration increases as the intrusive center is neared.

Dark Green Pyroxene (*Hedenbergite*).—Subsequent to the wollastonite came the formation of a very dark green pyroxene, well-crystallized in long prisms. In the Carmen tunnel examples of metamorphosed limestone, above described, this pyroxene was observed to replace the wollastonite bands (which alternate with red garnet bands, and are themselves the metamorphic product of limestone bands) readily, while the reddish garnet bands are relatively resistant. There thus results an alternation of garnet

and pyroxene bands, conforming to the original stratification. Analyses of the pyroxene indicate that it is a lime-iron silicate rich in iron-hedenbergite. The ready alteration of the lime-silicate to the lime-iron silicate, therefore, indicates a new change in the magmatic solutions, which now carried abundant iron as well as silica.

The hedenbergite is also found very frequently cutting the wollastonite, the reddish garnet and the pale-green pyroxene in veins of varying size; and seems to have replaced all of the earlier minerals. This again shows that the solutions at this period carried all the essential constituents of the hedenbergite. On the third level Carmen mine the hedenbergite was observed to replace blue limestone, no earlier silicates having formed here. Data in the Dolores mine indicate that this mode of formation of hedenbergite was very important.

The earlier lime-silicates were formed in crushed and shattered rock, and there is abundant evidence that this provided the openings along which they rose and circulated. There appear, however, to have been few definite channels. The zones followed by the hedenbergite, however, show the initiation of some persistent fissuring previous to the advent of this mineral. These fissures were, as observed in the Dolores mine, formed mostly along the main contacts, which trend northwest; although there is evidence of some north-and-south fissuring. Some minor northwest fissures, parallel to the contacts, were formed back in the intrusion, and here also the hedenbergite replaced the monzonite and the earlier silicates. As the amount of hedenbergite deposited was vastly less than that of the earlier silicates, its localization along the contacts on account of the preexisting fissures makes it more nearly a "contact" mineral than the older ones. The main fissuring and subsequent deposition of hedenbergite took place along the southwest contact; the northeast contact shows, except locally, hardly more than traces of this period of deposition. On the southwest contact the hedenbergite is frequently massive and abundant.

Dark (Andradite) Garnet.—Subsequent to the hedenbergite deposition but overlapping upon it somewhat came the formation

of abundant yellow to dark green garnets, having much the same localization as the hedenbergite. These latter garnets are distinguished from the reddish garnet of the early stage by the fact that even where they form a solid garnet rock, they are well crystallized, while the garnet of the early stage appears to the naked eye amorphous. These later garnets are easily attacked by atmospheric alteration, to which the earlier garnet rock is very resistant. Analyses indicate that the later garnets are probably essentially lime-iron silicates, or andradites, while the earlier garnets are probably grossularites. The later garnets have developed largely along the contacts, especially the south contact of the Dolores intrusion; and for the same reasons of previous fissuring as the hedenbergite; like the hedenbergite, they often form by direct alteration of limestone, but may be found cutting through and replacing the earlier minerals, especially wollastonite.

Quartz, Fluorite and Cupriferous Pyrite.—Subsequent to the main garnet deposition, but overlapping upon it, were deposited fluorite, quartz, actinolitic hornblende, a little adularia, and abundant metallic sulfides of copper and iron, all practically contemporaneous. The hornblende was largely, if not entirely due to the alteration of hedenbergite. The dark green andradite appears sparingly in this group, as a practically contemporaneous but really slightly earlier mineral, indicating the gradual transition of conditions from the earlier stage; indeed in this relation the largest and most perfect crystals of andradite are found, embedded in fluorite and calcite. A key to the relation is found in certain microscopic veinlets where layers of garnet were first formed next the walls, and the rest of the fissure filled with quartz, and metallic sulfides.

Mr. Fenner remarks "Quartz is the most important of all the minerals in regard to the ore-deposition. In repeated instances it is found in such intimate association with the sulfides that little doubt can exist of close genetic connection. It is believed, in fact, that the deposition of quartz was practically contemporaneous with that of the ore, though it may have begun a little earlier."

These conclusions, that the chief sulfide deposition immediately followed the lime-silicate period, with quartz as principal gangue,

form an independent corroboration of the conclusions reached at Velardeña.[1]

Epidote as a result of the direct metamorphic processes is certainly not abundant. Mr. Fenner's studies led him to believe that it had formed in small quantity. He found evidence that it replaced the grossularite garnet and the vesuvianite and must therefore be at least slightly later than they. In one secion it is probably replaced by quartz. In another, vesuvianite and garnet are cut by a vein containing quartz, orthoclase, cupriferous pyrite, calcite and a little epidote.

In Dr. Wright's description of Spec. 59 (p. 470), prehnite, zoisite and epidote seem to be closely related to one another, and to calcite.

Mr. Fenner describes in two thin sections a mineral which is probably apophyllite, occurring in veins with fluorite, calcite, and quartz and later than wollastonite.

The materials of the stage last mentioned gained access to the localities where we find them through definite fissures, which were much more strong and persistent than any previous ones; but they were also deposited by replacement, not only of limestone, at the margin of the metamorphic belt, but by replacement of earlier silicates. The quartz is regarded by Mr. Fenner as the most important non-metallic mineral of this stage, but the fluorite was also very important.

Metallic Sulfides Other than Those of Iron and Copper.—The quartz-fluorite-sulfide stage passed into various substages marked by changes in the metals deposited as sulfides. Fluorite is most characteristic of the beginning of this series; the later-deposited sulfides may or may not be accompanied by quartz, with occasional fluorite.

Calcite.—Somewhat later than this stage, but overlapping, came the crystallization of calcite, which gained access through new fissures. Mr. Fenner finds evidence from his microscopic work that the calcite has replaced pyroxene, wollastonite, and other earlier silicates. In certain slides wollastonite is intersected by veins of calcite, which shows a tendency to develop in

[1] Economic Geology, Vol. 3, No. 8, 1908, p. 724.

the midst of wollastonite fibers and replace the masses gradually throughout. In No. 15 (a metamorphosed monzonite) garnet and pyroxene have been cut by a vein of wollastonite, which later has become partly replaced by calcite. Mr. Fenner remarks "Calcite appears to have replaced the siliceous minerals of the series with the greatest facility. Probably the reaction by which limestone is converted into a mass of silicates when basic oxides and silica are introduced by solutions at high temperatures is one which is easily reversed at low temperatures, with the re-formation of calcite and removal of the silica."

Increasing Proportion of Openings in Rocks.—The minerals of the quartz-fluorite-metallic sulfide stage form numerous fissure-veins in the monzonite transverse to the contact, and are capable of important subdivision as to age. The fissures of this period also occurred along and parallel with the contact, and therefore the materials of this stage mingled with or replaced the earlier minerals, or were deposited as plain veins cutting through them.

The same remarks apply to the various later substages of the metallic sulfide period; and to the calcite stage, where the fissures are unusually well-marked. Indeed one of the most interesting sidelights on this long succession of metamorphic minerals is the evidence that the size of rock openings gradually increased from first to last—from a condition where the shattered rock showed no continuous fissuring to one where large and persistent fissures were developed. A gradual lessening of pressure suggests itself as the explanation, and in this case the differences indicated are very great. If, as seems likely, this pressure was that of overlying rocks, which were gradually removed by erosion during the process, then the whole process of contact-metamorphism occupied an immense period of time. The time occupied by the ore-deposition, with all its various stages, was a very short segment of this total period.

The initial rupture formed by the Great Fault, as well as a few minor faults which occurred at the same period, were healed by calcite probably belonging to the last stage of metamorphic products mentioned above. This fixes the initiation of the fault-

ing as immediately subsequent to the ore-deposition. That this calcite was not deposited by atmospheric waters is indicated by the fact that the veins thus formed were shattered by the later and main movement of the fault, and that this later breccia-zone remains uncemented, although data above given indicate that the unfilled openings must have existed during a very long period.

Following this line of reasoning, it appears that the mountain block began to rise when the downward pressure of the weight of overlying rocks, as it was lessened by erosion, reached the point where it was weaker than the upward pressure of the solidified igneous rock column below.

Composition of Metamorphosing Solutions.—The most important point that has been established (and this has been definitely established by both field and microscopic work) is that the progress of contact metamorphism presented a consistent sequence of events, and that each stage was accompanied by phenomena of a definite character.

The established sequence may be summarized as follows:

1. Pale green, nearly white aluminous pyroxene.
2. Pale reddish aluminous garnet (grossularite) and vesuvianite.
3. Wollastonite.
4. Dark green lime-iron pyroxene (hedenbergite).
5. Yellow-brown, and dark green lime-iron garnet (andradite).
6. Fluorite, quartz and metallic sulfides (and actinolitic hornblende).
7. Metallic sulfides (and quartz and fluorite).
8. Calcite.

Each of these stages as we have seen, behaved as an independent invasion, intruding rocks of greatly varying composition—such as limestone and monzonite, for example—and replacing them. Each, except perhaps No. 1, and certainly the vesuvianite of No. 2, showed a certain preference for the limestone; but the fact that all likewise replace monzonite and other materials shows that this preference was primarily based on physical grounds, the solubility of the limestone making it more

readily susceptible of replacement. Each of these stages worked more or less powerfully on the products of the preceding stages as a corrosive and replacing agent. The agents of metamorphism in each case obeyed the laws of solutions—they rose through small fissure openings in the rock, and penetrated the rock along microscopic or submicroscopic channels. We must admit from their behavior as above stated, that the solutions at each period contained all the essential components of the characteristic minerals deposited at that stage. The composition of the attacked rock certainly exercised some influence, inviting or repelling to a certain degree the formation of a given mineral; but this consideration is of minor importance. The process has been in the main one of metamorphism by substitution.[1]

In the field, stages 1 and 2 of pyroxenes and garnets form a natural group, contrasted with stages 4 and 5 of pyroxenes and garnets, the two groups being separated sharply by the wollastonite stage. The 1–2 stages are colorless to pale-colored, showing evidently very little iron—not more, perhaps, than may have been contributed by the iron of the rocks which they replace, and, in the case of the stage 1 pyroxene replacing the monzonite, probably less. The 4–5 stages are dark colored, showing evidently a large excess of iron over the earlier rocks replaced. In the 1–2 stages crystallization is much suppressed, in the 4–5 stages it has been relatively free. The 1–2 stages are abundant and widespread; the 4–5 stages are quantitatively represented by only perhaps 1 per cent. as much rock as the 1–2 stages, and the distribution is more restricted, usually to the immediate vicinity of the *limestone* contacts. The 4–5 stages are, as indicated in the above table, closely associated with the copper sulfide deposition —the 1–2 stages have only the most remote connection with it—not more so, for example, than the intrusive rock itself.

Following is a series of analyses[2] showing the composition of the minerals at the different stages.

The first table is a series of alteration products from limestone.

[1] Same conclusion reached as in the Velardeña district. Vol. 3, No. 8, 1908, p. 711.

[2] All these analyses are by Booth, Garrett & Blair, of Philadelphia.

Specimen No.	(70)	70	67	Wollastonite, Theoretical.	68	69
Silica, SiO_2	(11.08)	6.65	36.98	51.7	43.26	34.68
Alumina, Al_2O_3	(0.85)	0.51	15.50		3.01	2.20
Iron oxide	(0.62)	0.37				
Ferric oxide, Fe_2O_3			5.00		1.73	25.61
Ferrous oxide, FeO			2.04		23.11	1.80
(Pyrite), FeS_2					2.15	
Manganese oxide, MnO			0.09		0.66	0.14
Lime, CaO	(86.33)	51.80	34.89	48.3	19.93	32.54
Magnesia, MgO	(1.03)	0.62	1.60		1.25	0.72
Soda, Na_2O					0.21	
Potash, K_2O					0.10	
Ignition		40.02				
Sulphur Anhydride, SO_3		0.10				
Total	99.91	100.07	96.10		95.41	97.70

This series is from the Carmen tunnel locality, above described.

70, blue limestone; *67*, red (grossularite) garnet which has replaced 70; *68*, dark green pyroxene (hedenbergite) replacing wollastonite and red garnet; *69*, dark green to yellow-brown garnet (andradite) cutting both 67 and 68.

(70) is the approximate composition of 70, when the carbon dioxide ("ignition") is driven off.

The widespread alteration of limestone in all its phases is attended by the complete liberation of the carbon dioxide. The alteration to red grossularite garnet (70 to 67), shows an increase of silica, alumina, and iron, a decrease in lime, and practically no change in the magnesia. The alteration of limestone to wollastonite shows an increase of silica, and a decrease in lime. The alteration of limestone to the later (hedenbergite) pyroxenes (70 to 68) shows an increase of silica and iron principally and a loss of lime; and the same is true of the change from limestone to andradite garnet (70 to 69). The alteration of grossularite to wollastonite shows a loss of alumina and iron and an increase of silica and lime; the replacement of wollastonite by hedenbergite and andradite is essentially marked by an increase of iron at the expense of silica and lime.

Spec. 67 was examined microscopically by Dr. F. E. Wright. The thin section shows principally gray and flesh-colored garnet in relatively large isotropic grains. Some of the crystal edges

show weak birefringence. There is considerable vesuvianite, colorless pyroxene, calcite, quartz, and a little wollastonite.

Spec. 68 was examined by Dr. Wright. The mineral is colorless to pale green in thin section. It is probably an unusual type of hedenbergite, noteworthy because of its high color, high refractive indices and its strong birefringence.

Spec. 69, examined microscopically by Dr. F. E. Wright, proved to be mainly green garnet (which was practically pure in the material obtained for analysis). Some of the garnet crystals were strongly developed, with the rhombic dodecahedron modified by the icositetrahedron. The garnet shows a remarkable zonal structure. The centers are pale green and isotropic; the margins pale flesh color and relatively strongly birefracting. These garnets have the high refractive index (1.83). Fine colorless pyroxene prisms, and calcite, occur as accessories, and rare epidote, quartz, and cupriferous pyrite.

The following table is a series of alteration products from the monzonitic rock.

Specimen No.	60	59	62	63	64
Silica, SiO_2	58.36	50.79	59.04	35.07	39.94
Alumina, Al_2O_3	19.75	19.89	17.28	18.90	5.72
Iron oxide	7.43	4.21	3.21		
(Ferric oxide), Fe_2O_3				8.00	9.65
(Ferrous oxide), FeO				1.31	2.33
(Pyrite), FeS_2					
Manganese oxide, MnO					0.10
Lime, CaO	7.05	19.75	10.61	35.33	34.70
Magnesia, MgO	2.29	2.25	2.48	0.85	1.93
Soda, Na_2O	2.88	2.85	2.43	0.19	
Potash, K_2O	2.19	0.47	4.89	0.25	
Ignition sulphur anhydride, SO_3					
Total	99.65	100.21	99.94	99.90	94.37

Nos. 60 and 59 are from the same small block from the Carmen tunnel. Nos. 62, 63 and 64 are from one locality, in the Gonzales tunnel (near by the Carmen).

60, relatively fresh monzonite; *59*, pale-green pyroxenic alteration of monzonite; in veins cutting 60; *62*, pale-green pyroxenic alteration of monzonite; *63*, red garnet and vesuvianite, alteration of 62; *64*, red garnet, alteration of 62.

The alteration of the monzonite (60) to the familiar and widespread pale-green pyroxenic phase (59 and 62) is attended by a loss of iron, silica and potash, and an increase of lime. Alumina remains about constant. The alteration of monzonite to the red-garnet vesuvianite stage (60 to 63 and 64) is marked by an increase of lime, and a decrease of silica.

In the alteration to 63, the alumina remains unchanged; in the alteration to 64, it has diminished. The alteration of the pale-green pyroxenic product to the red garnet-vesuvianite product is marked essentially by a sharp decrease of silica, and increase of lime, while there is also a less but still marked increase of iron.

A comparison of the 70–67 and the 60–63, 64 analyses shows that the same grossularite was derived from replacement of a limestone and a monzonite respectively. Comparatively speaking, in the first instance silica and alumina (and iron) were added, and lime removed; in the second, lime was added, and silica removed, the iron and alumina remaining nearly stationary. The solutions therefore carried silica, alumina, and lime.

This series was examined microscopically by Dr. F. E. Wright.

Spec. 60. Shows phenocrysts of plagioclase, hornblende, and biotite. The plagioclase ranges in composition from andesine to labradorite. Zonal structure is prominent, the crystal centers being richer in anorthite and frequently altered and replaced by hornblende and calcite. The fairly coarse plagioclase of the ground-mass also exhibits zonal growth and range in composition from oligoclase to andesine. Orthoclase, relatively little altered, is quite abundant. Quartz is infrequent. The amphibole shows zonal structure, the centers being brown, the margins green. Some of this green hornblende occurs in patches of fine needles, resembling uralitic hornblende. The biotite phenocrysts are fairly fresh and are red-brown. At several points in the section fine veinlets were observed, filled with hornblende and some biotite.

Some chlorite was observed as an alteration product of the hornblende.

Spec. 59, which represents the alteration of No. 60 along

belts bordering fractures, shows the hornblende and biotite completely removed. The rock is uniformly gray. The plagioclase phenocrysts show the same zonal structure, ranging from bytownite in the center to andesine at the margin; and the same is true of the relatively coarse plagioclase crystals of the groundmass. Plagioclase forms the predominating mineral. Colorless pyroxene appears abundantly as the result of metamorphism. Prehnite[1] occurs frequently in sheaf-like aggregates replacing and later than the plagioclase. Colorless zoisite and some epidote are scattered. Calcite is fairly common.

Specimen 62, which is of similar nature and origin to 59, but from a different locality, shows the same characteristics. There is a tendency toward holocrystalline porphyritic texture in this rock. The basic centers of the feldspar crystals are often replaced by epidote, while the smaller crystals are little altered. Colorless pyroxene (the result of metamorphism) is fairly abundant, and is often twined after 100. Secondary replacement products are calcite and zoisite, often grouped together.

Spec. 63. Shows garnet, wollastonite, and vesuvianite. The garnet is pale flesh-colored, and of high refringence. Calcite, chlorite, and pyrite were noted.

Spec. 64. Shows mainly flesh-colored garnet with some pyrite. The garnet is isotropic. Colorless pyroxene is evenly disseminated, in small grains. Wollastonite and calcite are fairly common, the latter often accompanied by quartz. Calcite and quartz were evidently formed after the lime-silicates had been precipitated.

Analyses 59 and 62 indicate that the pale-green pyroxene of stage 1 may be an aluminous leucaugite, mingled with residual material from the monzonite; the reddish garnet of stage 2, as indicated by its physical characteristics and the analyses (67, 63 and 64), is grossularite, or calcium-aluminum silicate. Vesuvianite is a basic calcium-aluminum silicate.

The pyroxenic alteration (stage No. 1) was accompanied by a decrease of iron; the grossularite alteration by a return of iron.

[1] Optical properties γ about 1.635, α about 1.615; biaxial, optically +, $2E$ fairly large.

It is doubtful, however, in the case of the altered monzonite, whether the grossularite carries necessarily more iron than the original rock, as a comparison of analyses 60 and 67 shows; and as the mass of stage 1 is greater than stage 2, it seems highly probable that the iron leached during stage 1 from the monzonite was sufficient to account for all the iron deposited during stage 2.

During the early part of the activity of these silica-alumina-lime solutions, therefore, they took iron into solution from the rocks through which they passed; during the latter part, they became no longer capable of holding this iron, and reprecipitated it.

Wollastonite (Stage No. 3) is a pure lime-silicate. At this stage, then, the solutions had changed, and contained principally silica and lime. That the transition from the aluminous solutions to the non-aluminous solutions was probably gradual is indicated by the occurrence mentioned on p. 460.

With stage 4, however (dark green pyroxene, analysis No. 68), we evidently have a large excess of iron. The analysis corresponds with the iron-lime silicate, hedenbergite, relatively pure. Stage 5 (dark-green garnet) represents the same kind of solutions. Analysis No. 69 shows a relatively pure iron-lime silicate, or andradite. It is noteworthy that in the hedenbergite, the iron is almost entirely ferrous, in the andradite almost entirely ferric.

An analysis[1] of a specimen (G74) of the pale-colored variety of garnets of stage 5, of a yellow green color, yielded 10.3 per cent. Fe and 7.9 per cent. Al_2O_3, 33.6 per cent. CaO, 1.0 per cent. MgO and 34 per cent. SiO_2. This is evidently an andradite (iron-lime silicate), relatively low in iron and with some of the grossularite molecule. The grossularite molecule may be residual from the earlier aluminous silicates (including grossularite) which this andradite has probably replaced.

The solutions for stages 4–5, then, had changed from those of stage 3 by the addition of abundant iron. They contained principally silica, lime, and iron.[2]

[1] *Compañia Metallurgica Nacional,* Matehuala.

[2] As a mass analysis bearing on this point, I am informed by Mr. Samuel James, manager of the smelter which reduces these ores, that the slag con-

For stage 6 the solutions were still principally silica, lime and iron. The hornblende which occurs here as a characteristic alteration of pyroxene is probably actinolite—an iron-lime silicate, like the hedenbergite from which it is mainly derived. At this stage also, we get evidence of highly volatile elements in the solutions, which, if they existed earlier, were not precipitated—fluorine and sulphur—and also of copper.

In stage 7 the solutions were still, at the beginning, principally silica, lime, and iron, with, as will be shown, other metals in succession taking largely the place of iron—first copper, then arsenic (with silver and gold), then zinc, then lead (with silver).

In stage 8 the silica and iron had practically disappeared from the solutions, which contained principally lime.

ORIGIN OF METAMORPHOSING SOLUTIONS.

To recapitulate, the following changes in the metamorphosing solutions are shown:

A. Alumina-silica-lime.
B. Silica-lime.
C. Silica-lime-iron (and other metals).
D. Lime.

The lime is the only element which persists throughout. Its derivation in part at least from the limestone suggests itself. The solutions have acted most vigorously along and near the contacts at all depths; the intrusions are in all cases intricate, and have engulfed blocks and islands of limestone of all sizes. It is inevitable, therefore, that solutions, traversing and replacing this limestone at depths below those studied should in any event have become calcareous. If, therefore, we eliminate the lime, we have the following sequence of solutions to account for

A. Alumina-silica.
B. Silica.
C. Silica-iron (and other metals).

tains less than 1 per cent. alumina. As the fluxes added are slight, this applies practically to the ore. Since probably 50 per cent. of the ore consists of these stages 4 and 5 green silicates, it is seen that as a whole they are remarkably free from alumina.

The alumina can hardly be explained as leached from the monzonite, for instead of increasing in amount with the duration of metamorphism, it decreases and disappears. The silica also finally disappears, with the prolongation of metamorphic action. The same argument cannot be applied to the iron and other metals, but had the iron of the later stages been derived from leaching of the ferromagnesian minerals in the monzonites, the solutions would probably also have contained much magnesia, in which, however, they are evidenced to have been notably lacking by the lack of magnesia in the later pyroxenes. That the solutions were individual and independent magmatic products, derived from the same deep-seated source whence the monzonite rose, seems probable.

Correlation with Alaskite-Quartz Magma.—It is now commonly recognized that in the process of differentiation of a magma, the siliceous end-product passes from the granitic stage through the alaskite stage to the quartz stage (as represented in crystallized form)—that is, the magma becomes poorer in iron and magnesia, and subsequently in alumina, till its more stable constituents are reduced mainly to silica; and these differentiation products are common as dikes or veins among the intrusive after-products, especially of granitic or monzonitic rocks. The ultra alaskitic (usually aplitic or pegmatitic in origin and structure) or alaskite-quartz magma would be an alumina-silica-alkali magma which passes into the quartz (alkali?) magma from which quartz veins of pegmatitic or alaskitic origin are deposited; and this, except for the alkalis, would correspond with the change noted from *A* to *B* above. Is it possible, then, that the changing metamorphosing solutions of contact-metamorphism as exhibited in this district are originally identical with the changing alaskite, alaskite-quartz, quartz magma? It has always been argued by Mr. Spurr that the alaskite-quartz magma was highly attenuated, and composed mostly of water and other highly mobile materials: is it possible that it is so highly attenuated as indicated by these contact-metamorphic phenomena? An occurrence noted a few years ago by Mr. Spurr, near Descubridora, Durango, Mexico, in the course of a detailed study of the copper-bearing contact

metamorphic deposits at that place, seems to answer this question. The main intrusion of granite or monzonite is large and without limestone inclusions, occupying a valley a mile or more in width. Running across the whole intrusion, a remarkably straight and persistent aplitic alaskite (quartz and feldspar) dike was found, and was followed with some curiosity to the limestone contact. At this contact it ended in a considerable mass of lime-silicates, although the contact on both sides showed no metamorphism for a long distance. Evidently the lime of the limestone had greater affinity for the silica and alumina of the alaskitic magma-solution than did the alkalis—lime-alumina silicates were formed, and the alkalis remained in the residue. The only indication that we have at Dolores of alkalis in the solutions is the deposition in very small amount, of the pure potash orthoclase, adularia, in stage 6, and the probably nearly contemporaneous hydrous lime-potash silicate, apophyllite, which occurs rarely.

In this connection also we may reflect on the scarcity or lack of pegmatites or alaskitic aplites as intrusions in pure limestone. The writers at least have never seen them. It seems probable that this magma is too fluid to retain its individuality in contact with limestone, but must needs form lime-silicates.[1]

Hydrous Silicates.—The presence of small quantities of hydrous silicates is believed to be of considerable scientific significance. As described on p. 456, the hornstone resulting from the earlier stages of metamorphism in the Cobriza area, contains probable zoisite and considerable possible prehnite, as studied by Dr. Wright. In the Dolores area (p. 464) Mr. Spurr and Mr. Fenner found epidote associated with quartz, orthoclase, cupriferous pyrite, and calcite. Mr. Fenner also describes probable apophyllite in veins with fluorite, calcite, and quartz, and later than wollastonite. In spec. 59 (p. 470) Dr. Wright found prehnite zoisite, and epidote, apparently closely related to one another and to calcite in point of age.

[1] These conclusions correspond with those reached for the origin of the metamorphosing solutions in the Velardeña district. ECONOMIC GEOLOGY, Vol. 3, No. 8, p. 724, year 1908.

Although the data are not abundant, the general indications are that all these minerals may belong in large part to the early part of stage 6 (p. 466) and may be associated with orthoclase and hornblende, and the metallic sulfide deposition. Zoisite and prehnite are hydrous lime-alumina silicates, epidote a hydrous lime-alumina-iron silicate, apophyllite a hydrous lime-potash silicate. The orthoclase (adularia) is alumina-potash silicate; the hornblende (probably actinolitic) probably lime-magnesia-iron silicate.

The hydrous minerals represent a definite stage of the metamorphism, and not the latest stage, since Mr. Fenner notes evidence that epidote is probably replaced by quartz. They are therefore the work of the magmatic waters, even though they may have resulted in large part from the alteration of older minerals (prehnite from plagioclase, etc.) just as the hornblende appears to have been in part derived from the pyroxene hedenbergite. Brögger has noted zeolites in pegmatite dikes as products of the last period of crystallization.[1]

These observations of the connection of these hydrous silicates and their associated non-hydrous silicates in connection with copper deposits in and near a fairly siliceous intrusive rock are especially interesting in consideration of the fact that the same minerals often occur abundantly in connection with copper deposition in basic igneous rocks; and some light may be thrown on these deposits and their place in the scheme of ore deposition, by these meager Dolores data. As these minerals are largely alteration products, the basic igneous rocks would contain elements better fitted to produce a large quantity of these secondary minerals than would the more siliceous rocks, when operated on by the same magmatic waters.[2] The close association of fluorite and rare apophyllite at Dolores, as above noted, is of special interest, as both are fluorine-bearing minerals.

[1] Cited by W. Lindgren, ECON. GEOL., Vol. 6, No. 7, p. 671.

[2] See W. Lindgren, "Some Modes of Deposition of Copper Ores in Basic Rocks." ECON. GEOL., Vol. 6, No. 7, p. 687.

ORE DEPOSITION.

Ore Deposition in the Mountain Block.—Let us now examine more in detail the phenomena of metallic sulfide deposition, listed above as stages 6 and 7.

Period of Copper Deposition.—The first three stages are barren of metallic sulfides. Occasional specks of pyrite only emphasize this fact. This includes the earlier pyroxene-garnet depositions, and the wollastonite. Nor does the localization of the minerals of these periods give any clue to the localization of the copper deposits. The later green pyroxenes and garnets, however, are closely associated with the ore deposits and are always a hopeful sign when prospecting. It is probable that little if any copper-bearing sulfides were deposited at the same time as the hedenbergite; but it is certain that some of the cupriferous pyrite was deposited if not contemporaneous with some of the andradite, then at least at the very close of its deposition. The former is the more probable—the copper deposition, initiated at this period, crept on gradually. Its epoch of deposition was marked by the formation of actinolitic hornblende, and the earlier-formed sulfides are often intimately mingled with the hedenbergite and the andradite. The first deposits were of cupriferous pyrite low in copper—carrying only a few per cent.; but this material was deposited in great quantity. As the deposition proceeded the proportion of copper to iron grew, producing copper-bearing pyrite of good grade. A selected specimen of this ran 14 per-cent. copper. At this stage quartz and fluorite were the characteristic gangues.

It has been stated above that the hedenbergite-andradite deposition, frequently associated with cupriferous pyrite so as to form a low grade ore, proceeded from fractures along which the solutions of that period rose. These were generally parallel to the contact—the south contact—of the Dolores intrusion. This stage is almost unrepresented at the north contact. The ores with the fluorite-quartz gangue occupied still more definite fissures—most of these were along the contact, and mingled with the previously-formed lime-silicates and cupriferous pyrite, increasing the grade of copper in the ore; but some persistent fis-

sure-veins were developed in the monzonite. The most important of these is the Hundidos vein, striking N. 30 E. and dipping 22–35° N. W. This has been traced across the whole intrusion; its intersection with the north limestone at the contact makes the Hundidos ore-body, the most important ore-body on that contact. Within the monzonite itself it is striking, but not strong enough to be of economic value. The main deposition of copper was caused by reaction with the limestone. This vein has been reopened several times and cemented by metallic minerals of later periods of deposition.

Period of Arsenopyrite Deposition.—The fluorite-quartz-chalcopyrite deposition passed over gradually into arsenopyrite, with or without quartz and fluorite. Arsenopyrite is extremely common in metamorphosed monzonite, in small quartz veins.

Period of Pyrite and Pyrrhotite Deposition.—This arsenopyrite gradually passed into pyrite, which occurs most noticeably in plain fissure veins cutting across the Dolores intrusion. The most important one (S. Miguel vein) is shown at the N. W. end of the San Miguel tunnel, and strikes N. E. (N. 49° E.), dipping 45° N. W. It continues as a strong vein of pyrites 1 to 3 feet wide, across the whole intrusion. On its N. E. end, where it encounters the contact, it does not pass into the limestone, but spreads out along the contact as a body of pyritic ore, principally pyrrhotite. A number of these N. E. striking, N. W. dipping pyrite veins, of minor size, occur in this part of the San Miguel tunnel. A very small one, followed to the limestone contact on the south, opened out into several feet of pyrrhotite. Pyrrhotite has not been observed in the district except in contact with blue limestone; and the hypothesis has been formulated that the normal pyrite of the veins is here precipitated by reaction with the limestone, as pyrrhotite. This reaction of course must take place at a certain elevated temperature.

In this portion of the mine these pyrite veins have not been supposed to carry any values, as they contain little or no copper. The theoretical conclusions from the geological study, showing that these pyritic Dolores veins were the geologic equivalents of the highly argentiferous La Paz veins (p. 483), led to sampling

the Dolores pyritic veins for gold and silver, which it appeared had never been done, although the veins had been exposed for years. Two samples only have been reported at the date of the present writing: one from the strongest of these veins, called the San Miguel vein in our report, and showing 1 to 3 feet of pyrite; the second from a weaker vein nearby:

	Au, Gr. per Ton.	Ag, Gr. per Ton.	As, Per Cent.
1. From S. Miguel vein	6.8	1,220	6.1
2. From next vein to southeast	3.3	253	10.3

The high values of sample No. 1 puts this vein into the La Paz type from an economic as well as a geologic standpoint. The total gold and silver values for this sample are $25.23. Further sampling is being carried on.[1]

The pyrrhotite elsewhere has been assayed for gold, silver, copper, and nickel, and is found to contain a very little of the first three, and none of the fourth.

At an elevation of 2,265 meters, or 150 meters above the San Miguel tunnel, is an oxidized vein outcropping at the San Nicolasito workings, striking N. 45° E., and dipping 25° N. W., but steepening with depth. This is an oxidized vein with some quartz, and appears to belong to the series described in the San Miguel tunnel, into which general group its dip would carry it. The ore stoped from this vein ran high in silver, and was therefore noted as an anomaly in the mine. A sample taken by our party gave 800 grams silver. The Dolores copper ore, as shipped, runs 50–80 grams silver throughout.

Still higher up the hill a number of small veins showing oxidized sulfides, with or without quartz or fluorite gangue, show around 200 grams of silver. Different portions of one vein, striking N. 24° E., and dipping 80° N. W., in altered monzonite, gave the following:

[1] A subsequent report of 22 samples of the San Miguel vein showed an average of Au 4.5 gr., Ag 591 gr., Cu 0.24 per cent. These results establish these veins as of the La Paz type. Composite assays of this vein indicate that the gold contents fluctuate with the arsenic contents (3.6 to 10.4 per cent.), indicating auriferous arsenopyrite as a constituent.

Au, Gr.	Ag, Gr.	Cu, Per Cent.	Pb, Per Cent.	Zn, Per Cent.
66	160	1.74	1.6	1.2
13	80	.51	.8	

The Santa Rosa tunnel runs in from the Dolores property at an elevation of 2,275 meters, and strikes the veins of the Minas Colon y Anexas, at a point about 370 m. N. W. of the breast of San Miguel tunnel. One of these veins is reported by the engineer in charge, to be a narrow pyritic vein carrying in spots up to 1,500 grams silver, with very little else of value. This vein strikes N. 60° W. and dips N. E. and is near the weaker part of the Dolores intrusion.

It therefore appears that these pyritic veins carry a relatively large amount of silver locally.

Period of Blende Deposition.—The pyrite deposition passed over into the deposition of blende (blackjack). As a feature of this transition, pyrrhotite and blende have been noted intercrystallized and contemporaneous in a vein in limestone, in the Cobriza area. The blende, though very common, is less in amount than the metallic minerals described as preceding. In fact, the whole sequence of metallic deposition in the Dolores mine, from the copper deposition on, is marked by a progressive decrease in volume; and none of the succeeding metal depositions have much more than a scientific interest.

Usually the blende occurs as a separate deposition, evidently younger than the other minerals described. It has not been noted as forming large veins of its own, but has filled openings in the veins of the transverse N. E. series where these have been split subsequent to the earlier depositions. It also mingles with the ores on the contacts.

Period of Galena Deposition.—Galena is still rarer than blende, is not found crystallized with it, although occasionally closely associated; and is probably somewhat later. It was noted in some quantity in the Hundidos stope in the Dolores tunnel, where it cuts the chalcopyrite ore of the earlier stage.

Recapitulation of Stages of Deposition. The different stages

of the metallic sulfide deposition may then be recapitulated as follows:

a Chalcopyrite and pyrite.
b Arsenopyrite (slightly auriferous).
c Pyrrhotite and pyrite (may or may not be argentiferous).
d Blende.
e Galena.

The stages of earthy and metallic minerals may be viewed together in the following table:

1. Very pale green pyroxene (probably leucaugite).		
2. Reddish garnet (grossularite) and vesuvianite.		
3. Wollastonite (gold?), see p. 58.		
4. Dark green pyroxene (Hedenbergite).		
5. Yellow brown garnet. Dark green garnet (andradite).	Cupriferous pyrite	
6. Fluorite and quartz (hornblende).	Chalcopyrite	*a*
7. (Quartz and Fluorite).	Arsenopyrite	*b*
(Quartz and Fluorite).	Pyrrhotite and pyrite (argentiferous)	*c*
(Quartz and Fluorite).	Blende	*d*
(Quartz and Fluorite).	Galena (argentiferous)	*e*
8. Calcite.		

Ore-deposition in the Valley Block.—The history of ore-deposition above described pertains to the uplifted mountain block only. We have, however, in the district a very unusual condition. The Dolores intrusion and ore-deposits are cut off on the east by a great fault, which began just after the close of ore-deposition. This fault has relatively dropped the block to the east a minimum of 1,500 meters, or about a mile; the actual total drop has probably been much more. On account of the steep dip of the fault, the actual vertical drop is about the same. On the east side of the fault we find the same monzonite intrusions in shales and shaly limestones, and associated with ore-deposits. The monzonite intrusions are sometimes, but not always, accompanied by the development of considerable areas of lime-silicates.

1. The monzonite is always a fine-textured porphyritic rock on

the east; on the west it is a coarse-textured porphyritic to granular rock, showing the beginnings of magmatic differentiation.

2. There are no copper ores east of the fault. The ore-deposits are fissure-veins striking N. E. to east. They consist mainly of argentiferous pyrite.

Several of these mines were visited. The smaller ones are located not far from the fault—as near, indeed, as the apron of debris on the east side of the fault will allow prospecting. The Carmen mine is only a kilometer distant from the Dolores and the Carmen property adjoins the Dolores; the ores are argentiferous pyrite. Adjoining the Carmen on the east and about 2 kilometers from the Dolores are the mines at La Paz village, including the La Paz, Nueva Paz, Esmeralda, etc. These are deep mines, as is the Dolores. At La Paz the veins have been followed down for a depth of 525 meters; at Dolores the development extends over a vertical range, from the San Nicolasito workings to the bottom of the San Miguel shaft, of about 475 meters. The La Paz mines have produced millions of dollars worth of silver with no copper; the Dolores mines millions of dollars worth of copper, with only a very little silver.

The Esmeralda Mine.—The Esmeralda, a typical deep mine at La Paz, was visited. There is here a dike of quartz monzonite porphyry 25 or 30 meters wide in the calcareous shales, and running in an easterly direction. *No metamorphism was noted.* The veins are in the sedimentary rock, nearby. The main vein strikes N. 65–80° E., and dips S. W. 45–60°. Its width varies from a few inches to 10 feet, being frequently 6–8 feet. The essential mineral of the vein is pyrite, with a certain minor proportion of blende. The values are entirely in silver, which is evidently associated with or in the pyrite—no silver minerals are known. The values run from 500 to 1,500 grams. The ores average about 4 per cent. zinc. They are essentially no-gangue ores, although considerable calcite is associated with them in the veins, but in such a way that secretion from the wall rock seems certain. The blende is intercrystallized with the pyrite as though practically contemporaneous.

In another vein in the same mine, the argentiferous pyrite vein

had been split open a little and the fissure occupied by a small branching vein of later galena. Galena, however, appears to be no more common in this mine than in the Dolores.

The La Paz Mine.—The La Paz mine, according to Mr. James, the smelter manager, has veins which contain pyrite, arsenopyrite, quartz, fluorite and calcite. These ores carry a little blende and some galena. The chief values are in silver—running on the average from 400 to 1,600 grams. The silver does not vary with the proportion of galena and the inference is that it is in the pyrite. Gold is present in these mines in about the same amount as in the Dolores mines—usually 1½ to 2 grams. Mr. James noted that the amount of gold varied with the amount of arsenopyrite, as if the arsenopyrite were slightly auriferous; and this accords with Mr. Spurr's observations at the Dolores, that the arsenopyrite is slightly auriferous.

Comparison of Deposition Stages in Mountain and in Valley Blocks.—The Carmen and Esmeralda veins, then, correspond exactly to the *c* (*d*) (p. 481) stage of deposition at the Dolores; while the La Paz mine represents the (*b*) *c* (*d*) stage.

In this lower block are veins of the calcite period also; they form a north-east system, cutting across the east-west veins of the metalliferous period. In some of these veins celestite occurs in great quantity. The deposition of celestite slightly preceded that of calcite; the fissures were often filled with several feet of celestite, which was later split open, and the new fissure healed by calcite.

At the Dolores, however, the veins of the *c* period are small and (so far as yet known) of little commercial value; at La Paz they are large and of great importance.

Before the faulting, the bottom of the developed La Paz veins were vertically above the top of the developed Dolores copper ores (S. Nicolasito) by a calculated minimum distance of 600 meters.[1] The actual distance was probably much greater.

[1] These figures added to the figures on p. 482 give the minimum vertical range of deposition for the *a*, *b*, and *c* stages:

Developed range of *A*, see p. 484, stage at Dolores..... 475 m.

Genetic Relation of Dolores and La Paz Ores.—It will be noted that in the La Paz block east of the fault the stage of metallic deposition earlier than the (*b*) *c* stage is nowhere represented, so far as known. There are no copper ores known to the writer in this block. The subsequent stages represented in the valley are limited to and similar in importance to the last stages represented in the mountain block. The valley block sequence, in short, corresponds with the last portion of the mountain block sequence. Quantitatively, however, there is an enormous difference. In the mountain block the copper deposition (stage *a*) is so abundant that it overshadows all others; in the valley block the argentiferous pyrite (silver deposition), stage *c* has the same relative importance. In each case mines of the first degree of magnitude have resulted. The transition is suggested in the mountain block at Dolores, where silver-bearing veins of minor size and value begin to come in. Conditions, therefore favored the *c* deposition and prohibited the *a* deposition, at an elevation several thousand feet above another zone, where the *a* deposition flourished, and the *c* deposition is represented by only scanty later-formed veins. The upper zone we will then call the *C* zone, or the argentiferous pyrite zone; the lower zone the *A* zone or the cupriferous pyrite zone. As to what the determining conditions were, only one explanation suggests itself—temperature and pressure. The *A* zone was deposited lower down, at greater pressure and temperature; the *C* zone higher up, at less pressure and temperature.

Minimum of gap between top of Dolores and bottom of La Paz....	600 m.
Developed range of stage *C* at La Paz.....	525 m.
Minimum total	1,600 m.

= 5,248 feet = about 1 mile.

This is probably far short of the actual vertical range.

THEORY OF ORE-DEPOSITION.

J. E. SPURR.

In 1907 the writer outlined a theory of ore-deposition.[1] To this the reader is referred as a preliminary to the following discussion; also to subsequent papers on "Ore Deposition at Velardeña," and "Ore Deposition at Aspen."[2] One of the important features of this theory is that the metalliferous solutions from which ores are deposited originate in and spring from the zone of igneous rock differentiation, which is in the lower part of the zone of crystallization.

ORIGIN OF SOLUTIONS PRODUCING CONTACT METAMORPHISM.

The results of investigation contained in the present paper (which coincide with and carry further the conclusions arrived at in the Velardeña paper) indicate that at Dolores, contact metamorphism began after the intrusive rocks had become consolidated, so as to permit of extensive fracture, though under great pressure; that along these fractures the metamorphosing solutions rose from below, and attacked and replaced intruded and intrusive rock alike; that this process of metamorphism, or the deposition of lime-silicates continued for a very long period (this point well deserves to be emphasized), with definite stages indicating changes in the metamorphosing solutions. This much is established beyond question.

In this case, then, the common conception that contact metamorphism, or the formation of lime-silicates, is due to the effect of solutions pressed out and expelled from the immediately adjacent intrusive rock into the wall rock at the time of its consolidation, is regarded as an elementary one, not corresponding to the

[1] "A Theory of Ore-Deposition," Vol. 2, No. 8, ECON. GEOL.

[2] ECON. GEOL., Vol. IV., No. 4, pp. 301–320, 1909; and Vol. III., No. 8, pp. 688–725, 1908.

facts. In the course of a considerable field experience with these deposits, moreover, the writer has seen none where this conception seemed to apply. Much less is this the case with the metallic minerals associated with these lime-silicate deposits.

The close relation of the metamorphic deposits (lime-silicates) at Dolores to the intrusions indicates that the former ascended along or in the consolidated intrusions, and that they originated either lower down in these intrusions or at the same source whence the intrusions sprang. The Dolores intrusion shows within itself the beginnings of rock differentiation, the later portions being more siliceous. This is the process which normally leads to siliceous aplitic alaskites and pegmatites, and finally to pegmatitic quartz veins; and it seems likely that in greater depth the observed differentiation was carried further, and actually resulted in these end-products.

The inductive analysis of the solutions which produced the contact metamorphism at Dolores and Cobriza leads to the hypothesis that these solutions were indeed the same solutions or magmas whence siliceous alaskite and alaskitic (pegmatitic) quartz is deposited, but that they had absorbed lime from the limestone on their upward journey.

If this is the case, then the solutions which produce contact metamorphism originate in and spring from the zone of differentiation, which is in the lower part of the zone of crystallization.

CONDITIONS GOVERNING ADDITION OF LIME TO ALASKITE QUARTZ MAGMAS.

It appears probable that whether these siliceous residual magmas become calcareous by the time they have passed upward to their zone of precipitation depends on the size and solidity of the intrusion. In a large intrusive mass, the magma-solution may pass upward through the consolidated rock to the zone of deposition without having come in contact with calcareous rock. Deposition will then take place in this zone within the intrusion as alaskitic aplites and quartz veins; but on the contact, where the solutions encounter limestone, as lime-silicates. There will then be little or no metamorphism of the igneous rock. Where intru-

sions are small, however, or where they are complex, enclosing many engulfed blocks of limestone, as in the Dolores district, the magma solutions arrive at the zone of precipitation saturated with dissolved lime, and replace igneous intrusive, and intruded rocks alike.

The common localization of lime-silicates at the contacts of intrusive with calcareous rocks is therefore seen to be mainly due to the precipitative influence exercised by the limestone, and is not due to an expulsion of material from the intrusive rock. As a matter of fact, the evidence is that these metamorphosing solutions travel within and keep within the intrusive rock, by preference, for various, chiefly physical, reasons. The same observation applies in large measure to the copper ores of "contact metamorphic" deposits.

DEPOSITION OF MATEHUALA SEQUENCE DURING FALLING TEMPERATURE.

The sequence described at Dolores appears to be a regular one, and to have been attended by gradually falling temperature. The earlier deposition of silica and lime as wollastonite, and their later deposition as quartz and fluorite, indicate this.[1] The transition from the formation of pyroxenes to the formation of hornblende at the critical temperature of ore-deposition also indicates this, as the pyroxenes are known from experiment and observation to crystallize at a higher temperature than the amphiboles. In general, also, it seems quite certain that lime-silicates are formed at a higher temperature than the simultaneous deposition of quartz and calcite, or quartz and fluorite.

ORE-DEPOSITION A MAGMATIC PHASE.

This inference, then, of falling temperature during contact metamorphism also pertains to that part of the process charac-

[1] According to certain experiments in the dry way by A. L. Day, E. S. Shepherd, E. T. Allen, W. P. White and F. E. Wright, *Am. Jour. Sci.*, 19, 1905, pp. 93–134, and 22, 1906, pp. 265–302, on lime-silicate mixtures, wollastonite was formed between 800° and 1,180° C., and quartz only below 800° C.

terized by the deposition of the metallic minerals; the first of which were practically contemporaneous with the last lime-silicates. The sequence of metals *a, b, c, d, e,* therefore (p. 481), was deposited during falling temperature. At a given period the temperatures favorable for the *a, b, c, d* and *e* depositions, respectively, characterized distinct zones, one ranged successively beyond the other; and more or less vertically, as conditioned by the buried focus of heat far below and the earth's surface far above. With the progress of consolidation and cooling below, the temperature zones migrated downward; and types of metallic deposits which formed first only in a certain zone migrated downward, thus superimposing themselves on ore-deposits earlier formed in these lower zones. Thus are explained the types *b, c, d, e,* superimposed upon the predominant *a* type in the Dolores mine, and the *e* type superimposed on the (*b*) *c* (*d*) type at La Paz. The (*b*) *c* stage at La Paz, then, was deposited much earlier than the (*b*) *c* stage in the Dolores mine, and was probably contemporaneous with the *a* stage in the Dolores—each representing the first metallic deposit to form in their respective zones; and the scanty representation at the Dolores mine may be taken as an indication that at the *c* period in the Dolores mine, the solutions had become poor in metallic contents. This is further indicated by the fact that the *e* stage, representing a subsequent superimposed stage in both the Dolores and La Paz districts, is represented with equal scantiness in both districts, and is the last metallic stage to be represented.

It therefore appears that the period of metalliferous deposition taken as a whole was largely a magmatic phase, partially independent of temperature, and dependent upon a certain stage which had been reached in the differentiating magma in depth. The changes in the magmatic solutions registered by the lime-silicates whose formation preceded the ore-deposition, would largely have the same explanation.

There would therefore, result, in the regular series of after-products from a given body of differentiating magma in depth, metalliferous solutions, whose emanation would be restricted to a

certain limited duration. During the height of this critical period at Matehuala the temperature appears to have been fairly constant, or to have decreased very slowly, with the result that the zones of maximum deposition are situated one above the other and are distinct. The lowering of the temperature zones took place in the waning stages of the mineralizing period, and before the cooler temperature of stages of ore-deposition normally higher up than *e* had reached the La Paz horizon, the critical period of ore-deposition had entirely passed.

GENERAL DEFINITION OF PRINCIPAL ORE-ZONES.

In the original paper on ore-deposition above referred to,[1] the writer made a preliminary attempt to define the principal zones of ore-deposition; adding that it would probably be ultimately possible to subdivide these periods. He now submits a modified column, based on experience in the last four years.

A. The pegmatite zone, containing tin, molybdenum, tungsten, etc., with characteristic gangue minerals, such as tourmaline, topaz, muscovite, beryl, etc.

B. The free gold-auriferous pyrite zone, with coarse quartz gangue. (Principal gold zone.)

C. The cupriferous pyrite zone. (Principal copper zone.)

D. The zone of argentiferous pyrite and auriferous arsenopyrite. Either one may be represented to the exclusion of the other, indicating a subdivision of this zone. Silver may fail in the pyrite and gold in the arsenopyrite. (Principal arsenic zone.) A frequent mineral of this zone is pyrrhotite. Antimony may occur, especially as jamesonite. In certain metallographic provinces ores of nickel and cobalt occur in this zone. The ores of this zone are frequently without gangue.

E. The blende zone. (Principal zinc zone.)

F. The argentiferous galena zone. Silver may fail in the galena. (Principal lead zone.)

G. The zone of silver and also much gold, usually associated with metals which combine with them to make substances which

[1] ECON. GEOL., Vol. 2, No. 8, p. 791, Dec., 1907.

are undoubtedly highly mobile, and account for the relatively elevated position of the zone. These associated metals include antimony, bismuth, arsenic, tellurium and selenium. Characteristic minerals of this zone are tellurides and selenides of silver, gold tellurides, primary argentiferous tetrahedrite and tennantite, polybasite, stephanite and argentite. (Principal silver and gold zone.)

Zones *A*, *B* and *G* characteristically have their contemporaneous gangue far in excess, quantitatively, of the metallic constituents; in zones *D*, *E* and *F* the reverse is the case. This is an important distinction. Zones *B* and *G* are characteristically quartz veins, carrying minor quantities (except zone *G*, where very rich) of metallic minerals. Zones *D*, *E* and *F* are characteristically solid sulfide veins, carrying little or no contemporaneous gangue; but in many other cases they carry a good deal. The gangue is not characteristic, and is often wanting.

It is expected that further division of these zones will be ultimately possible.

C zone includes stage *a* at Dolores; *D* zone stage *b* and *c*; etc.

APPLICATION OF CLASSIFICATION TO CONTACT METAMORPHIC ORE-DEPOSITS.

It now appears that contact metamorphic ore-deposits fall into the above classification; the only observable difference being that by the absorption of lime from limestone in the magma, or by the reaction of the magma with limestone, the gangues become transformed from quartz to lime-silicates (down to a certain critical temperature below which quartz and calcite or fluorite form, instead of lime-silicates) without however, any noticeable effect upon the metallic minerals. The diversity of gangue thus effected however, enables a better record of changes of magma and temperature than the usual quartz gangue. Thus the temperature of zone *C* is fixed at the temperature for the passage from quartz and calcite (or fluorite) to lime-silicates; and of the passage from amphibole to pyroxene.

RELATIVE POSITION OF THE WOLLASTONITE ZONE.

The *B* zone as described above has repeatedly been described by the writer as including auriferous quartz veins which immediately succeed feldspar-bearing quartz veins, which in turn succeed pegmatites. Indeed some overlapping feldspar has repeatedly been found in veins of this type. Therefore these veins were formed just after the stage when alumina disappeared from the magma solution.

In looking over the table on p. 481 the writer noted that while zones *C, D, E* and *F* (p. 489) were represented, the earlier *A* and *B* zones were not. In considering the sequence of gangues, however, and the conclusions drawn as to the magma changes as described on p. 474, it was noted that the wollastonite deposition corresponded to the deposition from the siliceous magma, immediately after the disappearance of alumina as registered in the grossularite; that the grossularite should correspond to the quartz-feldspar deposits, and the wollastonite to the immediately succeeding gold-quartz deposits, which are typically almost free from iron or other metals. This deduction was at first only noted as indicating some flaw in the previous reasoning. Directly afterward, however, the following extract from an article by J. F. Kemp[1] on contact metamorphic ore-deposits was noted:

"Gold associated with wollastonite has been recorded from the Santa Fe mine, Chiapas, Mexico. It also occurs in the same relation, as I have observed in the Cane Spring Mine, in Western Utah. Even platinum has been detected by L. Hundeshagen, with the same mineral in a contact zone in Sumatra."

Platinum, it may be noted, is found in placers derived from the gold-quartz veins of California, British Columbia, and Alaska; and a platinum mineral, sperrylite, has been detected in a small gold-quartz mine in Algoma, Ontario.[2] All these gold-quartz veins belong to the *B* zone as above described.

Following the matter further, some samples of the wollastonite were taken in the Dolores mine. They resulted as follows:

[1] Mining and Scientific Press, Nov. 25, 1911, p. 679.
[2] Kemp, "Ore Deposits," 1903, p. 441.

Number.	Gold, Grams.	Silver, Grams.	Copper, Per Cent.
G 77	0	0	trace
G 81	7[1]	17	0.7
G 82	0	6	0.5
G 83	trace	6	trace

The only striking result was that of G 81, and so far as investigation of the methods of the assayer (who was not cognizant of the problem) could go, the assay received was accurate. The assay was of wollastonite veining in an area of metamorphosed monzonite of the early barren periods, a considerable distance from any copper deposits and from the contact. The fraction of a percent of copper shows some effect of this later mineralization, and is due to disseminated copper-bearing pyrite, which was later introduced, and could not easily be separated from the specimen. Inasmuch as the copper ores of the Dolores mine, however, regularly average about 1–2 grams of gold for about 3 per cent. of copper, and 50–100 grams of silver, it will be seen that this copper can not carry the gold, which is believed thus to belong to the wollastonite. This subject should be further investigated.

DISTRIBUTION OF LIME-SILICATE GANGUES.

Where the magmatic solutions meet or have met and dissolved limestone, temperature and pressure conditions are best in zone *C* (possibly also in zone *B*, as above indicated) for the formation of abundant lime-silicate gangue. Yet on account of temperature fluctuations and overlapping, lime-silicate gangues may sometimes appear as accompaniments of zone *D*, although usually in meager amount. The overlying zones are typically free from them; their temperature of deposition is so low that ordinary fluctuations are insufficient to form lime-silicates as accompanying and apparently contemporaneous gangues. It is probable that the deposits of zone *A* do not commonly migrate far enough from their birthplace in the igneous magmas to come in contact with limestones.

[1] Worth $4.20 per ton.

THE GARNET DEPOSITS OF WARREN COUNTY, NEW YORK.[1]

WILLIAM J. MILLER.

INTRODUCTION.

The principal garnet mines of the United States are located in Warren and Essex counties of the eastern Adirondacks, those of Warren county—especially the Hooper and Rogers mines below described—being the greatest producers. All of the Warren county mines are in its northwestern portion and within six or eight miles of North Creek village which is at the terminus of the Adirondack branch of the Delaware and Hudson Railroad.

GENERAL GEOLOGIC FEATURES.

The garnet mines of Warren county lie wholly within the precambrian rock area of the Adirondacks. The oldest rocks in the garnet region are the highly metamorphosed sediments of the Grenville series. Detailed mapping by the writer has shown extensive areas of Grenville which are unusually rich in limestone and closely associated hornblende gneiss.

Next in age come plutonic igneous rocks such as syenite, granite, and granite porphyry which are clearly intrusions into the Grenville and all of which are differentiation products from the same great cooling magma. Of these rocks the syenite is, perhaps, the most abundant. It is a medium to fairly coarse grained, generally quartzose and hornblendic rock with sometimes a more basic variety carrying a green pyroxene. The granite is highly quartzose and always contains hornblende or biotite or both. The granite porphyry is biotitic to sometimes hornblendic with large, pink, feldspar crystals imbedded in a fine to medium grained matrix. All of these rocks are distinctly gneissoid.

[1] Published by permission of Dr. J. M. Clarke, State Geologist of New York.

As a result of the great intrusion, the Grenville in some cases appears to have been pushed upward and to have been largely removed by erosion since; in other cases the Grenville was more or less engulfed by, or involved with, the molten flood as shown by the numerous inclusions and the areas of mixed gneisses; while in still other cases the Grenville rocks were left practically intact as shown by the large areas of pure Grenville.

Minor intrusives, cutting all of the above masses, occur as bosses or dikes of gabbro, pegmatite, or diabase.

An important structural feature is the presence of numerous normal faults which have greatly dissected the region.

DESCRIPTION OF THE GARNET DEPOSITS.

There are at least seven localities in Warren county where garnet mining has been carried on as follows: (1) Rogers (Barton) mine[1] near the top of Gore mountain and 3½ miles west-southwest of North Creek; (2) near the top of Oven mountain and 4 miles south of North Creek; (3) the Rexford mine, 1⅓ miles a little east of south of North Creek; (4) the Parker mine just southwest of Daggett pond and 4½ miles northwest of Warrensburg; (5) the Sanders Brothers mine near the mouth of Mill Creek and 2 miles east of Wevertown; (6) 2¾ miles north of North Creek; and (7) the Hooper mine just east of the northern portion of Thirteenth Lake. Of these, only the Rogers, Sanders Brothers, and Hooper mines are now in operation. The Rogers and Hooper mines lie within the Thirteenth Lake quadrangle and the others within the North Creek quadrangle. All of the above mines have been visited by the writer.

1. In the Rogers mine the mode of occurrence and the size of the garnets are of unusual interest. The matrix or rock carrying the garnets is a gray, medium grained gneiss which, in thin-section, shows: 20 per cent. orthoclase; 20 per cent. labradorite; 40 per cent. hornblende; 15 per cent. hypersthene; 3 per cent. biotite; together with a little magnetite and zoisite. Imbedded in this gray matrix are numerous, well scattered, translucent, reddish-brown garnets, those with diameters up to 5 or 6 inches

[1] This is called Moore's mine on the topographic map.

being very common, while the largest ones taken out are said to have been about the size of a bushel basket. These garnets, which are of the almandite variety, are always pretty badly crushed or coarsely granulated and they never show crystal outlines.

A remarkable feature is the never failing occurrence of a rim or envelope of pure, black, medium grained hornblende crystals which completely enclose each garnet. Occasionally a half inch

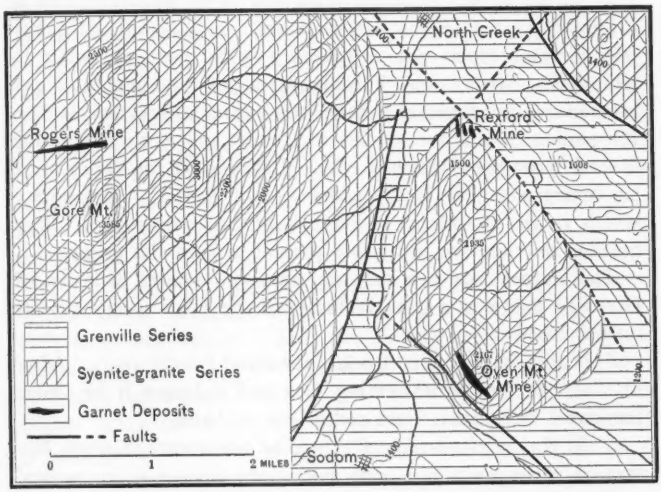


FIG. 68. Geologic and topographic sketch map of portions of the North Creek and Thirteenth Lake (U. S. G. S.) sheets, showing the mode of occurrence of those garnet deposits which are lens-like inclusions in the syenite or granite.

irregular mass of acid plagioclase or a crystal of biotite may lie between the garnet and the hornblende rim. As a rule the hornblende rims increase in width with the size of the garnets, some rims being as much as two or three inches wide. These reddish-brown garnets, completely surrounded by the black hornblende rims which are, in turn, imbedded in the gray gneiss matrix, present a striking appearance in the walls of the great mine pits.

This garnet bearing rock clearly occurs as a long, narrow, lens-like inclusion of Grenville gneiss in the great mass of Gore mountain syenite. The inclusion is fully three fourths of a mile long, with nearly east-west strike. Several large openings have been made in it and, in the very large more easterly pit, the width of the inclusion is more than 100 feet. The garnet rock is removed by blasting and reduced by sledge hammers after which the garnets are picked out by hand.

2. In the Oven mountain mine the mode of occurrence is precisely like that in the Rogers mine. In thin-section the matrix shows: 20 per cent. orthoclase; 25 per cent. oligoclase to labradorite; 50 per cent. hornblende; 2 per cent. biotite; 2 per cent. magnetite; together with a little pyrite, zoisite, and apatite. As compared with the similar rock from the Rogers mine the lack of hypersthene is noteworthy. Imbedded in the gray matrix are numerous, shattered, reddish-brown garnets (almandite) which range in size up to several inches in diameter. Black hornblende rims are invariably present around the garnets.

This garnet rock is a long, narrow, well-defined inclusion of Grenville gneiss in a granitic facies of the great syenite-granite intrusive body.

This mine has not been worked for about twenty years. After blasting out the garnet-bearing rock and reducing it by sledge hammers, the garnets were picked out by hand.

3. At the Rexford mine the type of occurrence is much like that of Oven mountain, only here there appear to be several smaller inclusions of the garnet bearing gneiss instead of one, and the country rock is a very gneissoid quartz-syenite. Garnets up to 5 inches across, always with hornblende rims, were noted. There are several mine openings but none have been worked for about fifteen years.

4. The old mine on the Parker farm occurs in a mixed gneiss area with granitic syenite and Grenville interbedded parallel to the foliation strike. These bands of rock are often 20 to 40 feet wide, one of them being made up of a nearly pure, granular, medium grained mass of irregular crystals of reddish-brown garnet and bright green pyroxene (coccolite?). About twenty

years ago this band of garnet rock was mined, crushed and put into barrels, there being no attempt to separate the pyroxene from the garnet.

5. At the Snaders Brothers mine the mode of occurrence is very similar to that of the Parker mine, the bands of Grenville being, however, somewhat less pronounced and numerous. The rock which is mined is pretty badly granulated and consists mostly of intimately associated reddish-brown garnet and green pyroxene (coccolite?) in small grains, with sometimes a little quartz and feldspar. There are some streaks or patches of nearly pure garnet. Work began in 1907 on the south side of the creek, but now all the mining is confined to the north side. The garnet-pyroxene rock is crushed, put into bags, and shipped to all parts of the world.

6. Years ago an attempt was made to mine the garnets which occur in the coarse, feldspar, biotite, garnet, Grenville gneiss 2¾ miles north of North Creek but this locality is of no special interest.

7. At the Hooper mine the garnets occur as crystals (dodecahedral) often with good crystal boundaries, up to an inch or a little more in diameter. They are thickly scattered through a medium to moderately coarse grained, dark to light gray, very gneissoid, hornblendic rock which has the composition of a basic syenite or an acidic diorite. It is important to note that these garnets never show the rims of hornblende. In fact the garnets may sometimes be almost surrounded by feldspar. This type of occurrence has not been observed on a large scale at any of the other localities within the county, though a rock almost exactly like it occurs at the Rogers mine as a distinct zone (wall rock) intermediate between the typical garnet-bearing gneiss and the country rock of syenite, where the garnet rock grades perfectly into the syenite. The significance of this fact will be explained below.

The deposit is an extensive one and a very large mine pit has been opened up. After blasting out the rock, it is somewhat reduced by sledge hammers, then taken on cars to the mill where it is crushed. By the use of an ingenious method, involving the

use of jigs, the garnet (almandite) is almost perfectly separated from the rest of the crushed rock which is of lower specific gravity than the garnet.

ORIGIN OF THE GARNETS.

All modes of occurrence of garnets observed by the writer on the North Creek and Thirteenth Lake sheets are summarized as follows:

1. As crystals or grains in various Grenville rocks, *e. g.*, the garnet-pyroxene gneiss; the hornblende-garnet gneiss; biotite-garnet gneisses, etc.

2. As distinct crystals frequently occurring in all types of intrusive rocks—syenite, granite, granite porphyry, and gabbro—except the diabase.

3. As large more or less rounded masses with distinct hornblende rims in the long, lens-like inclusions of Grenville hornblende gneiss in syenite or granite.

4. As more or less distinct crystals (dodecahedral), without hornblende rims, in a certain special basic syenite-like or acidic diorite-like rock.

In case number 1 (*e. g.*, Parker and Sanders Bros. mines) the garnets have, in the usual manner, crystallized out of masses of sediments under conditions of thermal and dynamic metamorphism. These garnets are rarely as much as an inch across and their origin presents no problem of special interest.

In case number 2 the garnets appear mostly to have crystallized out of the original magmas, their formation possibly having been due to some assimilation of Grenville sediment by the syenite or granite. The facts that these garnets occur so sporadically and that actual examples of local assimilation have been observed in the region strongly favor this view. Since these garnets seldom attain a diameter of an inch and are so scattered, no attempt has ever been made to mine them. Sometimes, as in the gabbros, the garnets have often been produced secondarily, or after the cooling of the magma, because they commonly form reaction rims around other minerals.

Case number 3 (*e. g.*, Rogers, Oven mountain, and Rexford

mines) is of particular interest because of the very large garnets surrounded by the reaction rims of hornblende.

Kemp and Newland[1] have briefly described a garnet deposit (formerly worked by the Messrs. Hooper) just across the line in Essex county less than a mile west of the village of North River and 4½ miles north of the Rogers mine. As judged by their description the type of occurrence appears to be similar to that in the Rogers, Oven mountain, and Rexford mines, though no mention of the hornblende rims is made. In conclusion they say:

> "The origin of this peculiar bed presents an interesting theme. The country rock is probably igneous. Its mineralogy and structure favor this derivation. The garnet rock must be either an altered form of a very impure limestone, or else a very basic igneous rock that was an original sheet or dike. The former supposition appeals more strongly to us."

Later Newland[1] says of the garnet deposits in general that:

> "The garnet is usually associated with a basic hornblende rock or amphibolite which forms bands and lenses in the more acid gneiss that constitutes the country rock."

In his brief description of the more recently worked garnet deposit of northern Essex county he speaks of the "amphibolite bands, which have been caught up during the intrusion of the anorthosite, or have been folded into the latter and metamorphosed."

From these statements we see that three possible modes of origin of these garnet bearing beds have been suggested, namely that they are: Lenses of sedimentary rock actually included in the igneous rock; or sediments folded into the igneous rock and metamorphosed; or sheets or dikes of very basic igneous rock. Now the work of the writer shows that, without question, these garnets occur in lenses of Grenville sediments which were caught up or included in the great igneous masses at the time of their intrusion. the tremendous heat and pressure being especially

[1] 17th An. Rep. N. Y. State Geol., 1897, pp. 548-9.
[1] N. Y. State Mus. Bul. 102, p. 71.

favorable for a very complete rearrangement and crystallization of the masses (inclusions) of sediment which were pretty low in silica. These inclusions are portions of a great thickness of hornblende-garnet gneiss, frequently interbedded with limestone, of the Grenville series. This gneiss is a basic rock generally carrying several per cent. of magnetite; sometimes considerable hypersthene; and little or no quartz. It is quite likely that some of the closely involved limestone was mixed with the inclusions of sediment during the process of metamorphism. It will at once be seen that such an iron-rich, silica-poor sediment was very favorable for the development of large garnets under the conditions of great heat and pressure which were brought to bear upon the lens-like inclusions in the molten syenite or granite.

The hornblende rims or envelopes are quite certainly great reaction rims around the garnets, but just at what stage of the metamorphism they were produced is not at all clear to the writer The rounded character of the garnets shows pretty clearly that the rims of hornblende are of secondary origin and that they were formed sometime after the crystallization of the garnets and possibly at the time when the pressure producing the foliation of the rocks of the region was brought to bear.

In case number 4 (Hooper mine) a clew to the origin of the garnets is furnished by a study of the wall rock in the Rogers mine on Gore mountain. In this latter case the typical garnet bearing rock (No. 1 of the accompanying table) of the mine passes by perfect gradation, through an 8 or 10 foot zone, into a basic syenite or acidic diorite (No. 2 of the table) which contains distinct dodecahedral garnet crystals up to over an inch across but always without hornblende rims. This rock, in turn, grades into a hornblende (quartzless) syenite (No. 3 of the table) which merges into the typical country rock of quartz, hornblende syenite, these two latter rocks being at times somewhat garnetiferous. The writer is fully convinced that this transition zone (wall rock) has been formed by assimilation or actual melting or fusing together of the syenite and the border of the great inclusion at the time of the intrusion.

TABLE SHOWING THE MINERALOGICAL COMPOSITION OF THE MATRIX OF THE GARNET-BEARING ROCK IN THE ROGERS AND HOOPER MINES.[1]

		Orthoclase.	Plagioclase.	Hornblende.	Biotite.	Hypersthene.	Magnetite.	Zoisite.	Apatite.	Pyrite.	Zircon.
Rogers Mine . .	1	20	Lab. 20	40	3	15	1	1			
	2	30	Ol.-an. 30	36			1	2	little	1	
	3	50	And 25	24				1	little		
Hooper Mine . .	4	42	Ol.-and. 20	30	5	2		½			½
	5	30	Ol.-and. 35	33	½	½	1				little
	6	40	Ol.-and. 20	35		4	1				

Now, as shown in the field, in hand specimens, and in thin-sections the garnet rock (Nos. 4, 5, and 6 of the table) at the Hooper mine is almost exactly like the wall or transition rock of the Rogers mine, and it also appears to grade into the country rock. In each case the garnets never show reaction rims of hornblende and the garnets often show good crystal outlines. In the Hooper mine this transition or intermediate rock makes up practically the whole mass which is mined and is thus much more extensive than at the Rogers mine. All evidence points to the origin of the Hooper mine rock as due to pretty thorough melting of an admixture of syenite and Grenville sediment where the Grenville inclusion was perhaps deeper down in the magma and hence subjected to much greater heat, or possibly a number of smaller hornblende gneiss inclusions, maybe with some limestone, were assimilated by the molten syenite.

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1906. NEWLAND, D. H. Mining and Quarry Industry of New York State. N. Y. State Mus. Bul. 102, pp. 70–73, and later annual reports on the mines and quarries of the state.

[1] A close approximation to percentage by volume only is intended.

DISCUSSION

This department has been established by the editors in order to afford to those interested in questions relating to economic geology an opportunity for informal discussion. Contributions are cordially invited either in the form of discussion of more formal papers appearing in earlier numbers or bearing upon matters not previously treated. Letters should be directed to the Editor, Sheffield Scientific School of Yale University, New Haven, Conn. The full name of the author should be attached to all communications.

THE PLANETABLE IN DETAILED GEOLOGIC MAPPING.

Sir: The paper on "The Planetable in Detailed Geologic Mapping," by F. L. Ransome, which appeared in the March number of ECONOMIC GEOLOGY is a valuable contribution to the subject of geologic mapping in that it brings definitely before the geological public the merits of the planetable in precise geologic work. Following Mr. Ransome's suggestion, some hints from eleven field seasons' planetable work in pure topographic, reconnaissance geologic, and detailed geologic mapping might be of interest. It is to those engaged in geologic work in more or less isolated and rugged mining districts that these remarks are particularly addressed, for, as has been repeatedly noted by the users of the planetable, this instrument is seldom used by mining engineers in mapping mining properties. The reasons for this are twofold; the technical schools do not teach the use of the planetable in such a way that the student can grasp its full possibilities, and there is an entirely reasonable hesitancy in undertaking new methods in the midst of the press of work with which the mining man is usually surrounded.

Mr. Ransome mentions the use of photographic enlargements of the original topographic field sheets for the use of the geological mappist. Having such a sheet at hand is fortunately and very properly the lot of those who are in the service of the

United States Geological Survey; but it should be remembered that a man thrown on his own resources in a new mining camp has not these facilities at hand. Under such circumstances the geologist is confronted with the problem of working out the detailed geology of a considerable area in a limited length of time. In a new and rough country the mining triangulation has not been extended far enough to be of use for control, and traversing is tedious and difficult, and even with the stadia it is inaccurate without special precautions. In the summer of 1911 such a piece of work was undertaken with the planetable as outlined below.

The problem was to map on a scale of 1,500 feet to one inch an area about one mile wide by five miles long. The maximum relief on this five square miles was between 2,300 and 2,400 feet; and the area extended over a pass about 2,000 feet above each of its extremities. The principal geologic feature of the area was an irregular contact between an intrusive basic granite and a sedimentary series. The country was fairly treeless and fairly easy to move around upon. In doing this geologic work a Bumsted, or "baby," planetable tripod was used. A light 18″×24″ drawing board was substituted for the usual 15″×15″ top. For sighting, a light and cheap Japanese telescopic alidade with stadia hairs, and vertical circle reading to 3′ was used. The straight edge on the alidade was eleven inches long. The weight of this outfit was twelve and one half pounds. In addition to the planetable and alidade were carried the usual impedimenta—hand-level, hammer, hand compass and clinometer, collecting bag, etc.; and an 8-inch peep-sight alidade carried in the hip pocket was very useful for secondary sights.

On the first day the south base, 1,475 feet (see figure 69), was measured with a 500-foot steel tape, and a reconnaissance triangulation net was laid out. This was done by "occupying" the ends of the base and likely stations, expanding the base very roughly. Bearings were taken with a Brunton compass, and in the field they were plotted to a small scale on a notebook page with a protractor. In this way the area was roughly laid out for control, although all the stations used later did not have to be

visited. The next day freshly hewn 3-inch square stakes were placed on all the points not already sufficiently marked by prominent rocks. Two assistants were used on the second day. On the third day the triangulation was expanded on the planetable and carried northward. Late in the afternoon of the fourth day the net was closed on the stations *O*, *P* and *Q* which had been located from the north base, 388 feet, by transit observations.

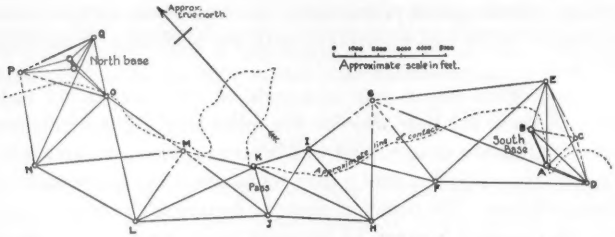

FIG. 69.

In this work especial care was taken to center the planetable over the stations and to extend all lines of sight on the paper. Stations *A*, *B*, *D*, *E*, *F*, *H*, *I*, *J*, *K*, *L*, *N*, *O* and *Q* were occupied. The sides of the triangle *OPQ* were computed from the transit observations and compared with the distances as scaled to one third of one fiftieth of an inch, or to the nearest ten feet, from the graphic work as developed from the south base. The results were as follows:

Line.	Computed Distances, Feet.	Scaled Distances, Feet.
OP	3,254.2	3,250
OQ	2,224.2	2,220
PQ	2,766.9	2,750

Thus the expense and the time necessary for an instrumental survey were obviated, and the accuracy of the work was well within that demanded by the geologic mapping. Vertical control was established throughout and numerous secondary points located.

The geologic mapping and the topography in 50-foot contours were then begun and carried on with the aid of one assistant

carrying a stadia rod. In many cases the assistant was sent to outcrops with rod and hammer to give a reading and to bring back a specimen. Although this system saved much climbing for the geologist it could be used only where inspection of the outcrop from the planetable made the character of the rock fairly certain, and it is not to be generally recommended. Magnetic stadia traverses were run at intervals as required and frequent checks on position were possible by the three-point location from known points.

The total time occupied in this piece of work was thirty days, and the time spent actually in the field was sixteen days. The total cost was about $175 or about $35 a square mile. This work was done in Korea, where the cost was probably somewhat less than it would be in the United States.

It must be borne in mind that a high degree of accuracy and speed with the planetable does not come without great care and practice in manipulation. For instance, the refinements of close scaling (traverses have been run in which the distances have been plotted to scale by the naked eye to less than 1/500 of an inch), of a properly sharpened plotting needle, of the wedge-pointed *hard* lead pencil, of the extension of the lines of sight on the edges of the paper, and of drawing lines from the *centers* of the *small* needle holes must be appreciated and acted upon in order to secure thoroughly satisfactory results. But even without much practice very fair and rapid results may be obtained.

With regard to the carrying of the planetable it may be said that some planetable users have noticed that after a few weeks in the field it is easier to get over rough ground with the planetable than without it. The reason for this is that the light tripod is often used as an alpine staff, and at other times the planetable can be used advantageously to balance oneself. In fact, one is conscious of a peculiar sensation of insecurity when in difficult positions without its friendly assistance.

And lastly, attention must be called to a characteristic of the planetable which has often been remarked upon in conversation by topographers but which doubtless has seldom found its way

into print. Anyone who has seen the topographer or geologist poring over the map on his planetable of an evening after a strenuous day's field work can realize that the planetable has risen from the rank of a mere scientific instrument to that of a creative instrument; for in addition to its scientific value the work of an honest and enthusiastic mappist is in the truest sense artistic and creative. Thus in the common cause of earnest effort to record Nature's truths the instrument and the man become in a way a part of each other. Often alone, and far from camp, the days and weeks spent together in the field, meeting common dangers and solving common problems, develop a feeling of comradeship which can scarcely be appreciated except by those who have had the experience themselves. The notebook can not rise to this degree of esthetic merit.

D. F. HIGGINS.

REVIEWS

Types of Ore Deposits. Edited by H. Foster Bain. Mining and Scientific Press, San Francisco, 1911. Pp. 378, illus. Price $2.00.

Of the 13 papers contained in this volume, 11 are descriptive of different types of ore deposition while 2 are of more general character. Some of the contributions are reprints of previous publications; others have been written for this volume, which presents in convenient form the latest conclusions of the authors regarding the form and genesis of the kinds of deposits described. Whether each particular deposit described constitutes a clearly defined type is a question perhaps more academic than practical. The book should be read with interest and profit by any student of ore deposition.

In the introduction, the editor has briefly sketched the historical development in this country of the knowledge of ore deposition, tracing the early predominance of the "lateral secretionists," the unduly rapid rise of the "ascensionists," the return swing of the pendulum illustrated by Van Hise's statement of the principles of ore deposition in 1900, and the present state of equilibrium in which each case is studied on its merits. Mr. Bain reviews briefly each of the contributions making up the book and adds pertinent and interesting comment.

C. H. Smyth, Jr., describes the Clinton and similar iron ores and reviews the replacement and sedimentary theories of their origin. The replacement theory holds that the iron was dissolved from the overlying shales and sandstones and, being carried downward, replaced the oölitic limestone. The author argues that this would give patchy deposits, not beds of the regular composition and distribution actually found, and that, furthermore, the descending solutions could hardly pass through and leave pure unaltered limestones such as are found above the ore beds and separated from them by a sharp plane. Finally, in the leaner ores very commonly the ferruginous center of an oölitic grain is surrounded by pure calcite the reverse of what should be expected under the replacement theory. The author concludes that the ore was deposited as the sediments were laid down and is thus a type of true primary sedimentary ore. He rejects the hypothesis that the original form of the iron was glauconitic on the grounds that the ore is nowhere found to grade into glauconite and that the ore is not glauconitic at depths of 1,000 feet

where if that were the original form of deposit one would hardly expect so complete a change to the oxidized ore as actually occurs.

C. K. Leith summarizes from U. S. Geological Survey Monograph LII the description and genesis of the sedimentary banded iron formations of pre-Cambrian age as the Lake Superior type of iron deposit. The average iron content of the total iron-bearing formations is about 38 per cent., whereas the iron content of the original rocks was 24.8 per cent., the difference representing the extent of secondary enrichment. The ratio of ore to total mass of iron formation in the different districts ranges from 0.062 per cent. in the Vermilion district to 2.0 per cent. in the Mesabi district. This difference is due largely to the structure of the districts, the flat-lying position of the Mesabi rocks more readily permitting secondary concentration. Among other structural features favoring concentration are impervious basements, particularly in the shape of pitching troughs, fracturing and fissuring of the iron formations. The ores are derived from iron silicate (greenalite) and cherty iron carbonate beds by oxidation and hydration producing ferruginous cherts that are primarily enriched by the leaching of the silica and secondarily by the addition of iron oxide and carbonate from other members of the formation. It is concluded that the iron-bearing formations, as indicated by their conformability and freedom from detrital materials, were subaqueous sediments, chemically precipitated, and a genetic connection with the associated ellipsoidal basalts is suggested.

H. F. Bain considers that the "flats" and "pitches," characterizing the lead and zinc ores of the Wisconsin district, constitute a distinct type and under that heading he has described the general form, structure, and composition of the lead and zinc deposits of the Upper Mississippi Valley, and pointed out their relations to the stratigraphy and structure of the rocks of the region. He restates (perhaps with less emphasis than is desirable, in view of the fact that one reviewer understands him to derive the ores from "overlying sediments") his conclusions regarding the genesis of the ore bodies, as published in U. S. Geological Survey Bulletin 294, arguing that the ores were drawn from the rocks of the region, transferred and concentrated by locally ascending waters under artesian pressure, and that the openings known as "flats" and "pitches" are due to the condensation of locally thicker basin deposits of the underlying "oil rock," the abundant organic content of which was the agent of precipitation of the metallic sulphides. The localization of the deposits in southwestern Wisconsin and contiguous territory rather than in seemingly favorable territory elsewhere is attributed to the paleogeographic relations of streams to sea coast.

The lead and zinc deposits of the Ozark region are discussed by the late Dr. E. R. Buckley. In brief, Dr. Buckley's theory is that the metals

of the ore deposits of the region were, before their present concentration, disseminated through the shales, of Pennsylvania age, which formerly covered all or nearly all the Ozark region. As the shale was eroded the disseminated metals were taken into solution as sulphates, carried downward into the underlying rocks, and there reduced to sulphides and deposited. The first of the sub-districts of the region to be described is the disseminated lead district of southeast Missouri, the chief lead-producing area of the United States. In this district perhaps 75 per cent. of the galena occurs as a dissemination, the remainder occurring in vugs, crevices, sheets, etc. The disseminated lead occurs as a replacement of the Bonneterre dolomite. Analyses show that the water ascending under pressure from the underlying Lamotte sandstone carries lead in measurable quantity as also does the water descending into the mines from the dolomite. The lead in the water from the sandstone is thought to be derived from the igneous rocks of the St. Francis Mountains, whereas that in the dolomite is supposed to be leached in part from the upper portion of the dolomite, and in part from higher formations. No specific mention is made of the Pennsylvanian shale as the principal immediate source of the lead, and it is not apparent whether Dr. Buckley meant to abandon the hypothesis suggested in his report on the disseminated lead district.[1] Basic dikes, intruded into the Bonneterre formation, are said (p. 104, footnote) to occur in two places in Ste. Genevieve County and to contain visible quantities of galena and sphalerite. Though basic intrusives fairly rich in lead and zinc have been noted in the pre-Cambrian rocks, this is the first announcement, so far as known to the reviewer, of undoubted intrusives in the Paleozoic rocks of Missouri. Dr. Buckley's discussion of the Joplin district follows the general trend of the report on the Granby Area by Buckley and Buehler and reiterates the conclusion that the lead and zinc, originally disseminated through the Pennsylvanian shale, were carried downward in solution into the limestones and cherts of the Mississippian where a commingling of the oxidized and reducing solutions resulted in the precipitation of the metals as sulphides. Similar conclusions are reached for the lead and zinc deposits of Central Missouri and North Arkansas.

A. C. Lane discusses native copper deposits with especial reference to the copper deposits of Michigan. He finds that such deposits are associated with red sediments which in turn are associated with basaltic lavas containing iron and a small percentage of copper. The copper is further associated with earthy chloride waters and with zeolites presumably deposited from hot waters. The conclusion is reached that the copper was leached out of the basalts by the chloride waters, was con-

[1] Mo. Bur. of Geology and Mines, Vol. IX., p. 225.

centrated by evaporation in the basins in which were laid down the deposits of red sandstone and, finally, was precipitated by a differential heating of the chloride solutions such as is indicated in the experiments of Fernekes.

The novel deposits of the Cobalt district of Ontario are described by the late S. F. Emmons. The conclusions, which are based on a few brief visits, are confessedly tentative and it is perhaps inappropriate to set this contribution in apposition with others that presumably represent the final word of their sponsors. There are two systems of fractures, one holding the cobalt ore and extending to considerable depths, the other, a later one, characterized by native silver content and by not extending below the Huronian rocks. The limitation of the richer ores to the Huronian, generally within 200 feet of the surface and rarely penetrating the Keewatin, is taken to indicate that the phenomenal richness of the veins is due to secondary enrichment which has reached downward only about 200 feet or so. The primary mineralization by ascending solutions is represented by the cobalt ores, the later native silver fillings resulting from the secondary concentration. The Canadian geologists who have studied the region believe, on the contrary, that all the ores have been deposited by ascending solutions.

Oscar H. Hershey contributes the article on the Treadwell mines, considered as the type of low-grade gold quartz deposits. He describes in very considerable detail the petrology of the mines and their environment. The ore is found in albite-diorite dike-like masses intruding meta-gabbro. The ore is richest where the dike is shattered and refilled with veinlets of calcite and quartz carrying pyrite with gold. The writer agrees with A. C. Spencer in ascribing the ore solutions to magmatic waters but suggests that the gold may possibly have been leached from the meta-gabbro.

The saddle-reef is treated, very appropriately, by T. A. Rickard, who has written much on that type of structure and who worked out its genesis independently though he was anticipated in his interpretation by E. J. Dunn. The manner in which the quartz "saddles" fill arched openings left by the competent strata in the axes of anticlinal folds, and the "false saddles" form in intersecting fractures is brought out clearly by a number of illustrations. The Bendigo saddle reefs occur on three anticlinals in an area 5 by 15 miles in extent. The anticlinals have been explored vertically to a depth of 4,500 feet and in one of them 30 "saddles" were found in a vertical distance of 2,300 feet, but many of the saddles are not rich enough to work. Some "inverted saddles" occupy analogous positions in the synclinals but they are small and unimportant. Very thin but persistent basic (limburgite) dikes pursue irregular upward courses through the axial planes of the anticlines. The

gold quartz is held to have been deposited by magmatic waters associated with the granitic intrusion connected with the deformation of the region, and these ores have been further enriched by solutions connected with the intrusion of the dikes.

F. H. Hatch describes the gold-bearing conglomerates of the Witwatersrand. The Witwatersrand formation consists of about 20,000 feet of slates, quartzites, and conglomerates, all probably of pre-Cambrian age. The auriferous conglomerates are mostly in the upper third of the formation and comprise four series, each made up of several conglomerate members. Of these, the lower or Main Reef series has been practically the only one to yield gold in workable quantity. It is about 150 feet thick and is made up of five "reefs" of conglomerates separated by beds of quartzite. The conglomerate consists of water-worn pebbles in a quartzose matrix of completely silicified sand. After the formation was silicified, it was elevated, folded and faulted and intruded by igneous dikes that were accompanied by magmatic solutions which accomplished extensive pyritization of the conglomerate and introduced the gold which field evidence shows to be genetically related to the pyrite. There has been some secondary enrichment by gold freed from the pyrite in the zone of weathering.

J. F. Kemp sketches the progress made in recent years in the study of contact phenomena, enumerates the characteristic minerals and points out the importance of contact deposits among the resources of copper and iron. The conditions most favorable to the formation of a contact ore deposit are brought about where a calcareous formation is intruded in depth by a large body of acidic magma. The question whether the magma has contributed material to the contact zone or not is considered at some length and decided in the affirmative on the evidence that contact zones are generally higher in alumina and iron, or in silica, than the unaltered wall rock. Field evidence corroborates this conclusion, in that the cavities and free space of the altered zone are not commensurate with the loss of volume due to recrystallization so that it is necessary to assume contribution from the magma. The chapter is a concise résumé of this phase of ore deposition.

The chapter on replacement ore-bodies, by J. D. Irving, is the longest paper in the volume. The characteristics of form and structure of such deposits and the criteria for their recognition are given with a wealth of detail and illustration which defies summary. It is a most helpful compilation. Attention should perhaps be directed to the argument (pp. 244–248) that solutions flowing in fissures are stagnated in front of impervious rock or other constriction with resultant widening of the ore-body. The velocity of flow must vary inversely as the cross-sectional area of the fissure, hence the velocity can not be smaller (*i. e.*, stagnated)

adjacent to the constriction than it is farther away, unless the fissure is larger near the constriction. The same principle applies to observations made in the chapter on "Some Causes of Ore-Shoots," near the bottom of page 335.

The paper on the outcrop of ore-bodies, by W. H. Emmons, is interesting in that while the other papers deal with the formation of ore-bodies, this one deals with a phase of their destruction, though this destruction may result in the formation of placers or in the enrichment of other parts of the same ore-body or of other ore-bodies. The topographic expression of lode outcrops is described in relation to their constitution, and the alteration and enrichment of gold, silver, and copper outcrops is considered in some detail, with many practical observations bearing upon the development and exploitation of such deposits.

The concluding chapter is a paper on "Some Causes of Ore-Shoots," by R. A. F. Penrose, Jr. The formation of ore-shoots is considered with respect to different metal-bearing agencies and precipitants, to structure and variation of fractures or other channels, to physical and chemical nature of wall rock and to superficial and deep-seated alteration. Examples drawn from the author's own wide experience lead him to the somewhat pessimistic conclusion that ore-shoots miss much more often than they hit the places where seemingly all conditions are favorable for their occurrence.

C. E. SIEBENTHAL.

SCIENTIFIC NOTES AND NEWS

RECENT REORGANIZATION within the Geological Survey includes the following distribution of administrative work involving some new appointments:

Mr. George H. Ashley, Administrative Geologist, to act as deputy to the Director and Acting Director.

Mr. Arthur Keith, in charge section of eastern areal and structural geology (east of the one hundredth meridian); Mr. T. W. Vaughan in charge of sub-section for the investigation of the geology of the Coastal Plain.

Mr. F. L. Ransome, in charge section of western areal and structural geology (west of the one hundredth meridian); Mr. E. S. Larsen in charge of sub-section for investigations and work relating to petrography.

Mr. W. C. Alden in charge of section of glacial geology.

Mr. T. W. Stanton in charge of section of paleontology and stratigraphic geology.

Mr. W. Lindgren in charge section of economic geology, metalliferous deposits.

Mr. H. S. Gale in charge section of economic geology, nonmetalliferous deposits.

Mr. David White in charge section of economic geology, eastern mineral fuels (east of the one hundredth meridian).

Mr. M. R. Campbell in charge section of economic geology, western mineral fuels (west of the one hundredth meridian).

C. W. HAYES spent the month of August with his family at Lake Winnepesaukee, N. H.

F. J. KATZ, of the U. S. Geological Survey, is completing the

[1] Geologists, mining engineers and others interested in applied geology are invited to keep the editor informed of new investigations of mining districts or scientific studies undertaken by them, together with such other scientific and personal items as may come to their notice.

geological survey of the Portland, Me., quadrangle. The work is coöperative between the state and federal governments.

L. M. PRINDLE, of the U. S. Geological Survey, is conducting geological studies in the slate belt of western Vermont and eastern New York.

T. NELSON DALE will spend the season in completing his study of the economic geology of the marbles of eastern Vermont.

H. M. EAKIN, of the U. S. Geological Survey, is investigating the placer deposits of the Ruby, Innoko and Iditarod districts, Alaska.

C. W. PURINGTON has gone to the Seward Peninsula, Alaska, to investigate placer deposits.

P. S. SMITH, of the U. S. Geological Survey, expects to study during the present season recent developments in the gold quartz deposits near Fairbanks, Alaska.

G. C. MARTIN is studying the effects of the recent volcanic eruptions on the mainland near Kodiak Island, Alaska, under the joint auspices of the U. S. Geological Survey and of the National Geographic Society. He will also make a reconnaissance of the mineral deposits of Kodiak Island.

A. G. MADDREN, of the U. S. Geological Survey, is attached as geologist to the party making a survey of the portion of the international boundary between Alaska and Canada extending from Porcupine River to the Arctic Ocean.

S. R. CAPPS and B. L. Johnson, of the U. S. Geological Survey, will conduct geological surveys during the present season in the Landlocked Bay-Ellamar copper region, Alaska.

F. H. MOFFIT, Theodore Chapin and J. B. Mertie will study during the present season the geology of the copper-bearing district between the Kotsina and Kuskulana rivers, branches of the Copper River, Alaska.

R. H. WOOD, of the U. S. Geological Survey, is making a geological survey of the Hominy quadrangle in the Oklahoma oil fields.

E. C. HARDER, who for the past two years has been engaged in the examination of certain iron ore deposits in Minas Geraes, Brazil, for an American company, was recently in Washington, D. C. He expects to return to Brazil in the near future.

BAILEY WILLIS sailed for South America in August to continue the supervision of geologic and topographic surveys for the Argentine government.

GEORGE C. MARTIN, of the Alaska Division of the United States Geological Survey, left Seattle, June 20, under the auspices of the National Geographic Society and the United States Geological Survey, for Kodiak, to investigate the recent volcanic activities on the Alaska Peninsula.

A. G. MADDREN, of the United States Geological Survey, is continuing his work of last year on the international boundary from the Yukon to the Arctic Coast.

GEORGE W. EVANS, mining engineer of Seattle, left early in June for a four months' trip to the Ground Hog coal field of northern British Columbia.

J. L. MCPHERSON, of Seattle, is making investigation of the mineral resources of the region tributary to the White Pass railroad in British Columbia.

H. M. EAKIN, of the United States Geological Survey, is spending the summer in the Ruby Creek and Ididerod placer camps in the lower Yukon basin.

PROFESSOR J. VOLNEY LEWIS, of Rutgers College, is spending the early part of the summer in the preparation and proof-reading of his new "Determinative Mineralogy," which is to be published by John Wiley & Sons in August. In general plan the book follows the well-known Brush-Penfield treatise, but it is intended to meet the requirements for a less encyclopedic and therefore simpler and less expensive work. By the elimination of excessively rare minerals the number in the tables has been reduced to 380 and the procedure has been greatly simplified.

Professor Lewis contemplates spending the greater part of the summer in mining regions in the West.

PROFESSOR NEWTON H. WINCHELL, of Minneapolis, for many years state geologist of the Minnesota Geological and Natural History Survey, has presented his geological library to the University of Minnesota. This library is probably one of the best private collections of geological literature in this country and was built up through the years when Professor Winchell, as editor of *The American Geologist,* had unusual opportunities for obtaining the earlier serial and regional reports of this and foreign countries. Many of its volumes are priceless. The library is now being installed in the Department of Geology at the University of Minnesota and will be known as the "Winchell Library of Geology," to which hereafter donations and exchanges should be addressed.

MR. BAILEY WILLIS returned to Washington late in June on furlough from his geologic work in Argentine republic.

F. B. VAN HORN sailed early in July from New York for Tampico, Mexico, where he will take up work with the Compania Mexicana de Petrolio "El Aguila," having resigned from his position as Geologist and Administrative Assistant in U. S. Geological Survey.

H. N. EATON (A.M., Harvard, '06, Ph.D., Pittsburgh, '12), instructor in geology in the University of Pittsburgh, has been appointed assistant professor of geology in the Pennsylvania State College.

DEAN WALTER R. CRANE, of the School of Mines, Pennsylvania State College, has been granted a year's leave of absence and left June 13 to spend the coming year in the study of the coal fields of Alaska and the northwest. Dr. Elwood S. Moore, professor of geology, will be acting dean during Dr. Crane's absence. Assistant Professor Thomas C. Brown, department of geology, has resigned to accept a similar position at Bryn Mawr College. Mr. H. N. Eaton, instructor in geology and petrography, University of Pittsburgh, has been appointed to succeed him. Associate Professor of Mining William M. Weigel has resigned to accept the position of general superintendent of the

North American Smelting Company, Ltd., Kingston, Ontario, Canada. Hugh D. Pallister, instructor in metallurgy, has been appointed to succeed Professor Weigel with the title of assistant professor of mining. Harry B. Northrup and William A. Royce have been promoted from assistants to instructors in mining. Carroll A. Garner has been appointed instructor in mining.

PROFESSOR MAYVILLE W. TWITCHELL, head of the department of geology in the University of South Carolina, has resigned to accept the position of assistant state geologist of New Jersey. He will reside in Trenton where he will take up his new duties early in July.

THE board of trustees of the University of Alabama at their meeting on May 30, 1912, relieved Dr. Eugene A. Smith, professor of mineralogy and geology, of active class-room work, in order that he might devote his whole time to the Geological Survey and to the up-building of the museum of Smith Hall, the new building named in his honor and devoted to geology and natural history. Dr. Smith is retained in the university as head of the department of geology and as director of the museum. The teaching is turned over to Dr. Wm. F. Prouty, professor of geology, and his assistants. This action of the board of trustees was based on the request of Dr. Smith and the recommendation of President Denny.

MR. OLIVER B. HOPKINS, who recently received his Ph.D. degree at Johns Hopkins University, has been appointed assistant state geologist of Georgia to fill the position made vacant by the resignation of Dr. T. Poole Maynard.

THE OIL RESOURCES of Barbados, W. I., which have long remained dormant, although known to certain London people, who made a desultory attempt at drilling about fifteen years ago, are likely to be soon brought to the notice of geologists and financiers by the recent action of the local government, who have ordered a geological survey and report to be undertaken. It is likely that Mr. Cunningham Craig, of Sir Doverton Redwood's office, London, who made the government report of the Trinidad

oil-field, will be engaged on this work. Mr. C. Craig is now in Trinidad, and is expected shortly in Barbados. As Mr. C. Craig has confirmed the opinion as to the identity of certain oil sands which occur in both islands, which was suggested by Messrs. Jukes-Browne and Harrison in their geological memoir of Barbados, the contemplated report is looked for hopefully.

N. H. EMMONS, engineer of mines, having severed his connection with the Tennessee Copper Company, wishes to announce that he has opened an office in the Union Oil Building, Room 917, in Los Angeles, Cal., where he will do consulting mining engineering.

DR. W. M. DAVIS has retired from the Sturgis Hooper professorship of geology at Harvard University. He will continue to reside at Cambridge. Professor R. A. Daly, of the Massachusetts Institute of Technology, has been appointed to the chair vacant by the retirement of Professor Davis.

DR. GEO. I. ADAMS has been appointed professor of geology in the Pei Yang University at Tientsin, China, and sailed from San Francisco on July 12.

PROFESSOR CHARLES E. DECKER, M.S. (Chicago), has been appointed assistant professor of geology and biology at Allegheny College.

THE degree of LL.D. was conferred on Professor A. H. Purdue, by the University of Arkansas, upon his retirement from that institution in June. For sixteen years he had been professor of geology there, and *ex-officio* state geologist of Arkansas since 1907. He is now state geologist of Tennessee.

AT the last annual commencement of Lehigh University the honorary degree of doctor of science was conferred on Dr. James E. Talmage, formerly professor of geology in the University of Utah.

WASHINGTON COLLEGE, Chestertown, Md., conferred the degree of doctor of science on Dr. J. S. Grasty, professor of geol-

ogy at the University of Virgina, at the annual commencement, when Professor Grasty delivered the address to the students.

A NEW office, that of administrative geologist, has been created on the U. S. Geological Survey, and Dr. George H. Ashley, Ph.D. (Stanford, '94), chosen to fill it. This position is virtually vice-director of the survey, placing the incumbent in complete charge of the organization during the absence of the director, and in addition giving him charge of certain functions of the organization the whole time. Dr. Ashley has been a geologist of the survey since 1901 except for the years 1910 and 1911, when he was state geologist of Tennessee.

THE following promotions to the rank of geologist of the U. S. Geological Survey have been made: Robert Anderson, B. S. Butler, Adolph Knopf, F. H. Moffit, G. B. Richardson and A. R. Schultz.

DR. CHESTER A. REEDS, for the past four years lecturer and associate in geology at Bryn Mawr College, has been appointed assistant curator of the department of geology and invertebrate paleontology of the American Museum of Natural History. He enters upon his new duties August first, after spending some weeks in Europe visiting museums.

MR. J. W. MERRITT, assistant in mineralogy at Northwestern University, has been appointed instructor in geology at Dartmouth College.

MR. R. E. GARRETT, of the University of Oklahoma and the Oklahoma Geological Survey, has been appointed assistant in mineralogy at Northwestern University.

THE UNIVERSITY OF GIESSEN has conferred on Mr. E. Leitz, Jr., director of the firm of Ernst Leïtz, Wetzlar, Germany, the honorary degree of doctor of medicine.

ALEXANDER N. WINCHELL has resigned from the United States Geological Survey in order to resume work as a consulting mining geologist. He has recently returned to his office in Madison, Wisconsin, after spending several weeks in Nevada in con-

nection with litigation regarding the ownership of the remarkable ore deposits of the National Mine in that state.

DR. T. POOLE MAYNARD, mining and consulting geologist of Chattanooga, Tenn., is now engaged in an investigation of the green slates of Georgia.